MISSOURI RIVER
DESIGN STUDY

LABORATORY INVESTIGATION
OF L-HEAD
CHANNEL CONTROL STRUCTURES
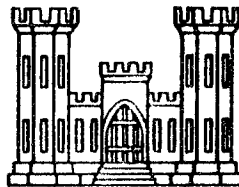
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U. S. ARMY ENGINEER DISTRICT, OMAHA

U. S. ARMY ENGINEER DISTRICT, KANSAS CITY

JUNE 1964

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In recent years flow regulation by completed upstream reservoirs and project advancement to the refinement stage induced field investigation which isolated a major cause of bed roughness as a result of open spur dike systems within the concave bank control structures. To reduce the cause and effects, a new type structure was designed which consisted of a longitudinal structure designed along the concave alignment which partially closed the gap between the open spur dikes.
Detailed design of this new structure called an "L-head" was varied in different areas to provide a basis for future analysis of field data to develop general design criteria. Realizing that this type of construction was still in its initial stage of development, a detailed laboratory design investigation using a model was requested. Such an investigation would provide faster results than prototype analysis and provide considerable savings over experimental construction of actual structures.

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MISSOURI RIVER DESIGN STUDY

Report on

LABORATORY INVESTIGATION OF L-HEAD RIVER CONTROL STRUCTURES

by

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Warren J. Mellema

June 1964

Acknowledgements

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(1) Franco, John J. "Hydraulic Models for Study of River Sedimentation Problems", Paper prepared for Federal Interagency Sedimentation Conference, Jackson, Mississippi, 1963.

(2) Einstein, H.A. "Similarity of Distorted River Models with Movable Bed", Unpublished Class Notes, University of California, Berkeley, California.

(3) Einstein, H.A. "The Bed Load Function for Sediment Transportation in Open Channel Flows", U.S. Dept. of Agriculture S.C.S., Technical Bulletin No. 1026, Sept. 1950.

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LIST OF SYMBOLS

Definition or Description

Symbol	Definition or Description
A	Cross Sectional area in square feet
D_{35}	Grain diameter at which 35 percent, by weight, is finer
D_{50}	Median grain diameter
D_{65}	Grain diameter at which 65 percent, by weight, is finer
g	acceleration of gravity
H	Vertical length, ft.
L	Horizontal length, ft.
L_x	Horizontal extent of the scour upstream of a structure
m	Subscript referring to model values
N	Number of points
n	Manning's roughness coefficient
p	Subscript referring to prototype values
Q	Discharge, cfs
R	Hydraulic radius, also referred to as R_T
R'	Hydraulic radius with respect to the bed grains
R''	Hydraulic radius with respect to the channel irregularities
S	Slope of the energy grade line and assumed parallel to the water surface
S_f	Density of the fluid
S_s	Density of the bed material
S_x	Standard deviation
V	Average velocity in feet per second
X	Vertical length ratio
x	Deviation from the mean
λ	Horizontal length ratio
ψ'	Intensity of shear on a representative particle

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General Investigation Abstract.

   a. Problem.

        In recent years flow regulation by completed upstream reservoirs and project advancement to the refinement stage induced field investigations which isolated a major cause of bed roughness as a result of open spur dike systems within the concave bank control structures. To reduce the cause and effects, a new type structure was designed which consisted of a longitudinal structure designed along the concave alignment which partially closed the gap between the open spur dikes.

        Detailed design of this new structure called an "L-head" was varied in different areas to provide a basis for future analysis of field data to develop general design criteria. Realizing that this type of construction was still in its initial stage of development, a detailed laboratory design investigation using a model was requested. Such an investigation would provide faster results than prototype analysis and provide considerable savings over experimental construction of actual structures.

        An overall objective of the design study was to determine if a movable bed model could provide the engineer with sufficient information to be used as a working tool. Specific objectives were to provide data that would assist in answering the following questions relating to L-head structures.

        1. What are the optimum design dimensions (length and height) of L-head structures?

        2. What is the most economical construction sequence for L-head structures?

   b. Discussion and Testing Outline.

        1. Model Section. Space limitations in the laboratory permitted modeling only the portion of the selected study bend which included the open spur dike system and a short portion of upstream revetment.

        The rate of sediment transport exerts a very strong influence on bed roughness and behavior of control structures. It was important that the model bed material be light enough to permit transport at very low velocities. Ground walnut shells were found to be the material which could best satisfy these requirements.

        2. Testing Outline.

        (a) Initial test runs were made to: become familiar with operation of laboratory equipment, develop suitable model structures, establish equilibrium sediment transport rates, establish instrumentation techniques and develop data recording procedures.

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(b) Existing structure systems vary in arrangement and curvature between bends. Areas of the concave bank controlled by open systems of spur dikes also vary both in dike spacing and location within an overall bend. With this in mind, it was apparent that two logical concepts in testing were possible and are summarized as follows:

(1) The effectiveness of the L-head length was studied as a function of the remaining gap or opening between the downstream end of the L-head and the next downstream structure.

(2) Also an approach to the length effectiveness could be studied as an accumulative effect where each opening between spur dikes would be closed by L-head extensions based on a percentage figure. This would result in a variable length of both the L-head and remaining opening within the spur system.

An infinite number of structure arrangements are possible if both length and height investigations were conducted concurrently. The limited period during which the laboratory was available necessitated adopting a test schedule which would first study the length problem with the top of the structures above the water surface. Results of the length testing indicated the most desirable lengths for height testing should be accomplished for L-head lengths closing 50% and 70% of the openings between dikes. Height testing considered an elevation range from one to nine feet below water surface.

c. Findings.

Analysis of laboratory data indicated that a minimum of 50% of the opening between spur dikes should be enclosed by L-head extensions. Data also revealed that the effectiveness of the L-head begins to diminish after approximately 65 percent of the opening has been closed. Spur dikes are unequally spaced within the bend and also vary between bends. Therefore, a special analysis, considering the total open area within a spur system, indicated that the total gap should be closed to within the range of 45% to 65%. Number and location of spur dikes is still a critical item to consider when applying this guide to other areas.

The findings must also be defined as applicable to bends of medium radii which range from 6,000 to 16,000 feet.

The data relating to the most economical height of L-head structures indicated very little benefit was derived by construction above the water surface. Data indicated that an equivalent of approximately three feet of moving water could be allowed to overtop the structure without affecting the efficiency of the L-head extension.

Observations and data from the various tests indicated that the initial 30% of L-head construction produces a very large influence on the flow patterns and significantly decreases the size of the scour holes at the end of spur structures.

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In areas where immediate total improvement is not critical, a possible construction phasing would result in a more economical construction.

The most surprising benefit obtained from the model was its ability to allow the engineer to actually observe the sediment being transported, dune patterns, bed waves, current boils, eddy currents, accretion build-up, bank erosion and consolidation of flow patterns. Modeling techniques have repeatedly proven to be effective in advancing sound economical designs. Here again, a very difficult type of model testing has demonstrated its potential as a successful engineers' working tool.

1. Introduction.

Construction on the Missouri River dates as far back as 1881 when local bank erosion protection was placed on a piecemeal basis. Work on a continuous project for bank stabilization and navigation began with authorization in 1927. The initial stage of development involves establishing the overall alignment in a series of bend curves by construction of structure systems composed of revetments and spur dikes. The final phase or refinement phase consists of designing and construction of training structures to provide the 300-foot width and 9-foot depth of the authorized navigation section of the open channel. The development during the refinement phase requires continuous studies, field investigations and design adjustments to insure that as construction progresses the accumulative effect of previously constructed control structures is considered in future designs.

It was initially intended during the early years of the project to completely revet all concave bends. Project economics and the theory that considerable bank roughness could be retained along the concave bank without serious effects resulted in leaving numerous systems of spur dikes exposed to channel flow. In recent years, flow regulation by completed upstream reservoirs and the advancement of construction on the project to the refinement stage induced studies that revealed a serious bed roughness existed which affected the navigational section of the open channel. A major influence on this roughness was resulting from the boundary roughness caused by the open spur dike systems. The stream lines entering a bend which contained open spur dikes impinged on each spur dike, developed a small water surface differential, and was deflected into the channel at an increased velocity with high turbulence, picking up bed material in its path and depositing it in locations of decreased velocity. This condition propagates a bed roughness that extends downstream for considerable distances and results in an inefficient and restricted channel cross-section.

This isolation of one of the causes of excessive bed roughness resulted in the design of a longitudinal dike extension, constructed along the designed curve which would reduce the boundary roughness and improve the flow lines through the bend. These structures were designed to reduce the cause and its effects and produce an acceptable channel x-section. To accomplish the refinement economically, the open area between the spur dikes was not completely closed. The resultant structure shape was similar to the alphabetical letter "L" and thus the extension was named "L-head".

2. Purpose.

Realizing that this type of construction was still in the initial stage and that the problem of detailed design was still in development, a laboratory investigation relating to L-head structure design was requested which would supplement field data obtained, provide faster results and provide considerable savings over experimental construction of the actual structures.

Investigation objectives actually became twofold. a. To develop laboratory techniques involving a movable bed model which would provide data needed to assist the engineer in the design of river control structures.

b. To apply the developed techniques in obtaining data which would assist answering problems relating to the optimum length and height in the design of L-head structures.

Other questions answered as a result of the study were potential applications of such a testing facility and construction procedures in river development.

3. Scope.

The Missouri River Bank Stabilization and Navigation Project covers approximately 735 miles. Within this length there are extremes in curvature radii from 3,200 feet to 25,000 feet and a vast number of combinations of control structures along the concave banks. Time was not available to study the many combinations of bend curvature and structure arrangements. The size of the laboratory facilities also were restrictive regarding the modeling capability of the flume. It was determined desirable to select a location which would be within the mid-range in curvature and possess a typical structure arrangement. Thus, the study results are only applicable to the average conditions. Additional investigations would be required to provide data on sharp or flat bends and peculiar structure arrangements.

The period during which the laboratory was available for this investigation was restrictive in that testing would be required to continue on an accelerated schedule with only a minimum of technical study of prior test results. Also, it would not be possible to double test all model conditions, which is a desirable laboratory technique. Conditions were re-tested only when a definite breach in experiment trends or imposed hydraulic conditions were noted. Data accumulated was the minimum necessary to accomplish the initial objectives.

4. Hydraulic Considerations.

a. Design of Movable Bed Models.[1],*[2]

The design of a movable bed model must consider the characteristics of the stream involved, the problem to be investigated, and the requirement that sediment transport in the model and prototype must be similar. Other factors that will affect the design are space and facilities that are available, and cost and time limitations. In attempting to design a model of a wide, shallow watercourse such as the Missouri River, the large horizontal dimensions and space limitations usually call for a model scale that is too small for use in the vertical direction. The shallow depths usually induce laminar flow, and the resulting hydraulic forces are not sufficient to create general movement of the bed material. In order to provide the greater water depth and additional slope, a vertical scale larger than the horizontal scale is often used. It is impossible to introduce one distortion alone, as a distortion of the linear scales affects the relationships of slope, velocity, width-depth ratio, curvature, and the distribution of energy within the channel. Also produced are changes in the size and shape of structures which in turn influence their performance. In the case of a movable bed model, still more distortions are introduced. For example, it is seldom possible to scale down the grain size distribution properly, and it is difficult if not impossible to

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*(1) Numerals in parentheses refer to corresponding items in the Bibliography.

obtain the proper relationship between suspended and bed load rates. As a result of these distortions, complete similarity between the model and the prototype can seldom be obtained. In order to obtain useful results, the distortion must be kept as small as practicable, and the reliability of the model must also be verified. This verification consists of adjusting the various hydraulic forces and model operating techniques until the model satisfactorily reproduces changes that have occurred in the prototype. After the model has demonstrated its ability to reproduce prototype conditions, results of testing still cannot be translated directly to the prototype. Instead, a base test or tests must be conducted against which the various proposals must be compared. In the case of this study, base tests with straight out dikes only and with complete screening of the concave bank formed the basis for comparing the results of tests on partial closure of the gap between spur dikes.
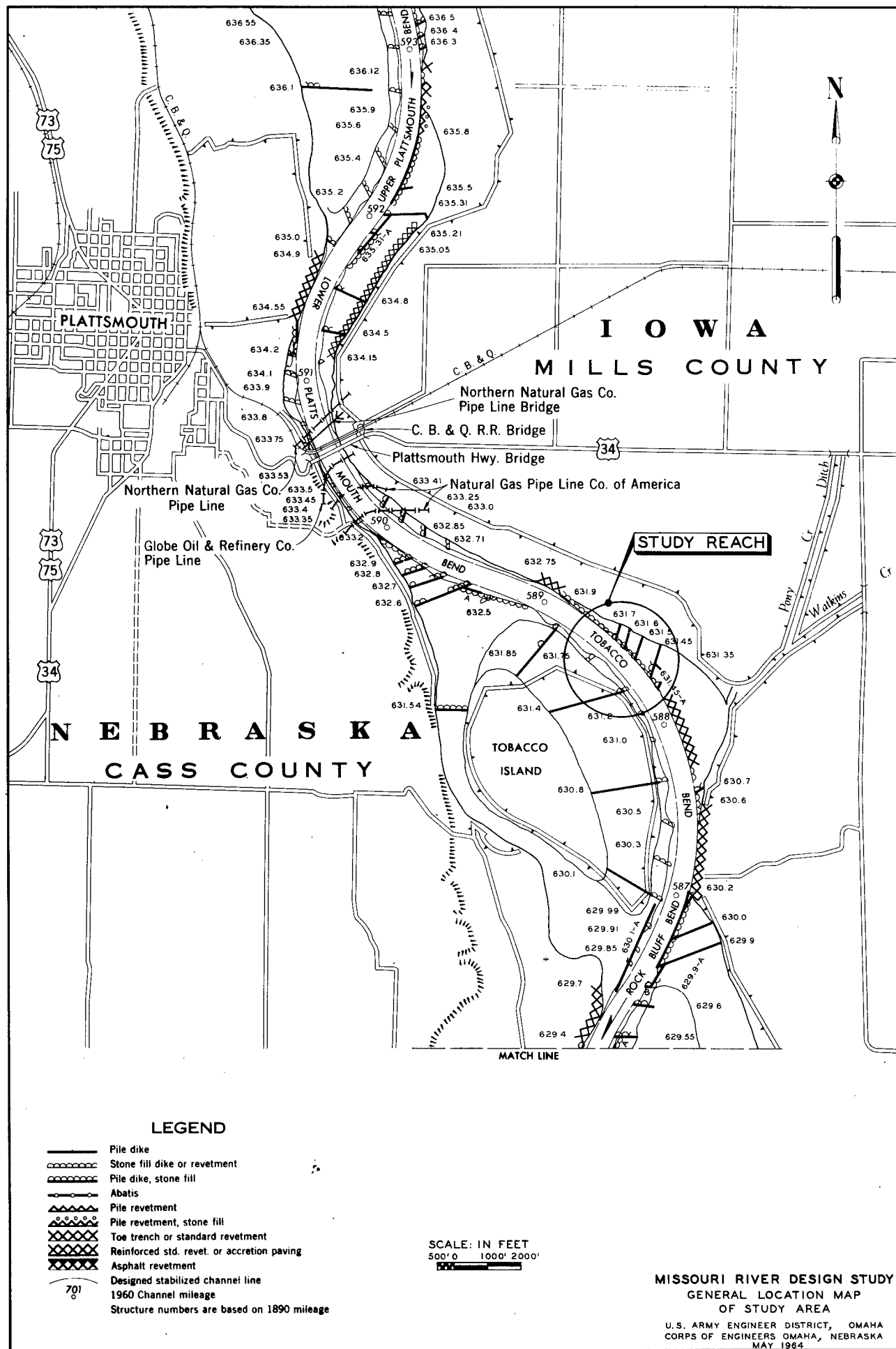
b. Selection of Test Area.

Before actual design of the model could proceed, it was necessary to select a representative portion of the prototype that could be satisfactorily reproduced in the model. Space limitations in the laboratory dictated that the system of structures selected should be fairly small in order to fit in the flume at a reasonable scale. The radius of curvature in the area should also be representative of a typical Missouri River bend. Also sufficient historical data should be available for use in verifying the performance of the model. An inspection of the Missouri River hydrographic maps indicated a system of structures in Tobacco Bend would be suitable. The map on Plate I shows the location of Tobacco Bend and the study reach. This system of four L-head structures was small enough to fit the available space, and sufficient survey data were available. Also the 6,800 ft. radius of curvature falls within the mid-range of radii in Missouri River bends. In addition, discharge measurements near the upper end of the reach were made in late November 1963. These measurements indicated the flow approaching the structures was quite uniformly distributed over the cross-section.

c. Scale Relationships and Hydraulic Data.

After selecting the study reach, it was then necessary to determine a suitable scale relationship between the model and the prototype. The 15-foot width and 30-foot length of the flume limited the maximum width of the model channel to about 5 feet. This model channel width gives a horizontal scale relationship of 1:120 for the 600-foot width between structures in the study reach. In order to avoid the previously discussed difficulties with shallow depths in the model, a vertical scale of 1:40 was arbitrarily selected for preliminary design purposes. Since gravitational forces predominate, Froude's law was used to determine the magnitude of hydraulic quantities to use in the model. Letting the symbol "λ" represent the ratio of horizontal dimensions and "X" the ratio of vertical dimensions, the following relationships can be developed:

$$\lambda = L_p/L_m = 120/1 = \text{horizontal length ratio}$$

$$X = H_p/H_m = 40/1 = \text{vertical length ratio}$$

6

N

636.55
636.35
636.12
636.1
635.9
635.6
635.4
635.2
635.0
634.9
634.55
634.2
634.1
633.9
633.8
633.75
633.53
633.5
633.45
633.4
633.35

636.5
636.4
636.3
593
592
591
590

UPPER PLATTSMOUTH
LOWER
BEND

C.B.&Q.

635.8
635.5
635.31
635.21
635.05
635.31-A

634.8
634.5
634.15

I O W A
MILLS COUNTY

Northern Natural Gas Co.
Pipe Line Bridge
C. B. & Q. R.R. Bridge
Plattsmouth Hwy. Bridge
633.41 Natural Gas Pipe Line Co. of America
633.25
633.0
632.85
632.71

C.B.&Q.
34

PLATTSMOUTH

Northern Natural Gas Co.
Pipe Line

Globe Oil & Refinery Co.
Pipe Line

MOUTH
PLATTS

73
75
73
75
34

633.2
632.9
632.8
632.7
632.6
632.5

BEND
589
588

632.75
631.9
631.7
631.6
631.5
631.45
631.35
631.5-A

STUDY REACH

TOBACCO

631.85 631.75
631.54

631.4
631.2

631.0
630.8
630.5
630.3
630.1
629.99
629.91
629.85
629.7
629.4

588
587

TOBACCO
ISLAND

630.1-A
630.9-A

ROCK BLUFF BEND
BEND

630.7
630.6
630.2
630.0
629.9
629.6
629.55

Ditch
Pony Cr
Watkins
Cr

N E B R A S K A
C A S S   C O U N T Y

MATCH LINE

LEGEND

▬▬▬	Pile dike
∞∞∞∞	Stone fill dike or revetment
∞∞∞∞	Pile dike, stone fill
─○─○─	Abatis
▲▲▲▲	Pile revetment
░░░	Pile revetment, stone fill
XXXX	Toe trench or standard revetment
XXXX	Reinforced std. revet. or accretion paving
XXXX	Asphalt revetment
────	Designed stabilized channel line
70¹	1960 Channel mileage
	Structure numbers are based on 1890 mileage

SCALE: IN FEET
500' 0   1000' 2000'

MISSOURI RIVER DESIGN STUDY
GENERAL LOCATION MAP
OF STUDY AREA
U.S. ARMY ENGINEER DISTRICT,   OMAHA
CORPS OF ENGINEERS OMAHA, NEBRASKA
MAY 1964

PLATE I

$$Q_p/Q_m = X^{3/2} = 30,360$$

$$V_p/V_m = X^{1/2} = 6.32$$

$$A_p/A_m = \lambda X = 4800$$

$$R_p/R_m = X = 40 \text{ for wide channels}$$

$$S_p/S_m = X/\lambda = 0.333$$

$$n_p/n_m = X^{2/3}/\lambda^{1/2} = 1.068$$

Where subscripts p and m refer to the prototype and model respectively and

Q = discharge in cfs

V = average velocity in ft/sec

A = area in ft^2

R = hydraulic radius

S = energy slope and assumed equal to water surface slope

n = Manning's roughness coefficient

In addition to the above, several relationships concerning roughness and sediment transport can be used as aids in verifying model performance. Einstein[3] and Einstein & Barbarossa[4] separate the hydraulic radius R into two parts, R' and R" with R' + R" = R. The value of R' becomes a measure of the hydraulic roughness due to the size of the grains that form the bed, and R" becomes a measure of the roughness due to the bars and other boundary roughness. R' may be determined from the following expression for the average velocity in the vertical:

$$V = 5.75 \sqrt{S R' g} \ \log_{10} \left(12.25 \frac{R'}{D_{65}} \right)$$

Where V, S & R' are as previously defined

g = acceleration of gravity

D_{65} = the grain diameter at which 65 percent, by weight, of the material is finer

Although it may not be possible to reproduce values of R' scale-wise, a similarity should exist if it is possible to obtain comparable values of the ratio R'/R between the model and prototype. A second relationship, which may be used to indicate similarity between model and prototype, represents the intensity of shear on the bed and may be determined from the following equation:[3]

$$\psi' = \frac{S_s - S_f}{S_f} \frac{D_{35}}{R'S}$$

Where ψ' = the intensity of shear on a representative particle

S_s = the density of the bed material

S_f = the density of the fluid

D_{35} = the grain diameter at which 35 percent, by weight, is finer

R' and S are as previously defined

Einstein[2] indicates that in order for the model and prototype to have similar sediment transport conditions near the bed, it is generally necessary for the ratio ψ'_p/ψ'_m to be equal to unity. An examination of the expression for ψ' will immediately show that if one uses the same bed material in the model as in the prototype, it will be virtually impossible for the values of ψ'_p/ψ'_m to even approach each other, as the small value of R'_m will make the value ψ'_m very much larger than ψ'_p. A logical way to make the ratio ψ'_p/ψ'_m approach unity is to use a light weight material for the movable bed in the model. In this study the values of ψ'_p and ψ'_m were made to approach each other by the use of finely ground walnut shells for the movable bed material in the model. A detailed discussion of this material is given in the section on model materials.

Hydraulic data for the prototype were computed from channel cross-sections obtained during the 1963 hydrographic survey, the discharge during the time of the survey, prevailing water surface slopes during 1963, and bed samples obtained from the general area during 1960 and 1962. Hydraulic data from the model were obtained during the preliminary adjustment of the model and from successive test runs. Table 1 presents a comparison of hydraulic data for the model and the Missouri River and indicates the degree of similitude that was obtained. Analysis of the data in this table shows that the vertical scale closely approaches 1:48 instead of the arbitrarily selected 1:40. The difference in ψ' values might seem to indicate that similarity of bed transport did not exist. However, if one considers that the value of ψ'_m would be approximately 30 had sand been used for the model bed material, the similarity of sediment movement is much more apparent. In view of the problems associated with movable bed models, it is concluded that the model well reproduced prototype conditions.

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TABLE 1

Comparison of Model and Prototype Hydraulic Data

	Missouri River	Theoretical $\lambda = 120$ $X = 40$	Actual Model Run No 19*	Theoretical $\lambda = 120$ $X = 48$
Discharge – cfs	33,000	1.088	0.827	0.83
Average Area – ft^2	7,250	1.508	1.327	1.258
Average Velocity–ft/sec	4.55	0.722	0.623	0.659
Channel Width – ft	600	5.00	5.00	5.00
Average Depth & Hydraulic Radius – ft	12.1	0.302	0.260	0.251
Water Surface Slope – ft/ft	0.0002	0.0006	0.0007	0.0005
Manning's "n"	0.025	0.0234	0.0258	0.0207
R'	4.18		0.064	
R'/R	0.347		0.246	
ψ'	1.13		6.81	
Specific Gravity of the Bed Material	2.65		1.33**	
D$_{35}$	0.18mm		0.27 mm	
D$_{50}$	0.20 mm		0.32 mm	
D$_{65}$	0.23 mm		0.36 mm	

*Run 19 shown since it represents the existing conditions in Tobacco Bend
**Saturated & Surface Dry

5. General Layout and Preliminary Testing.
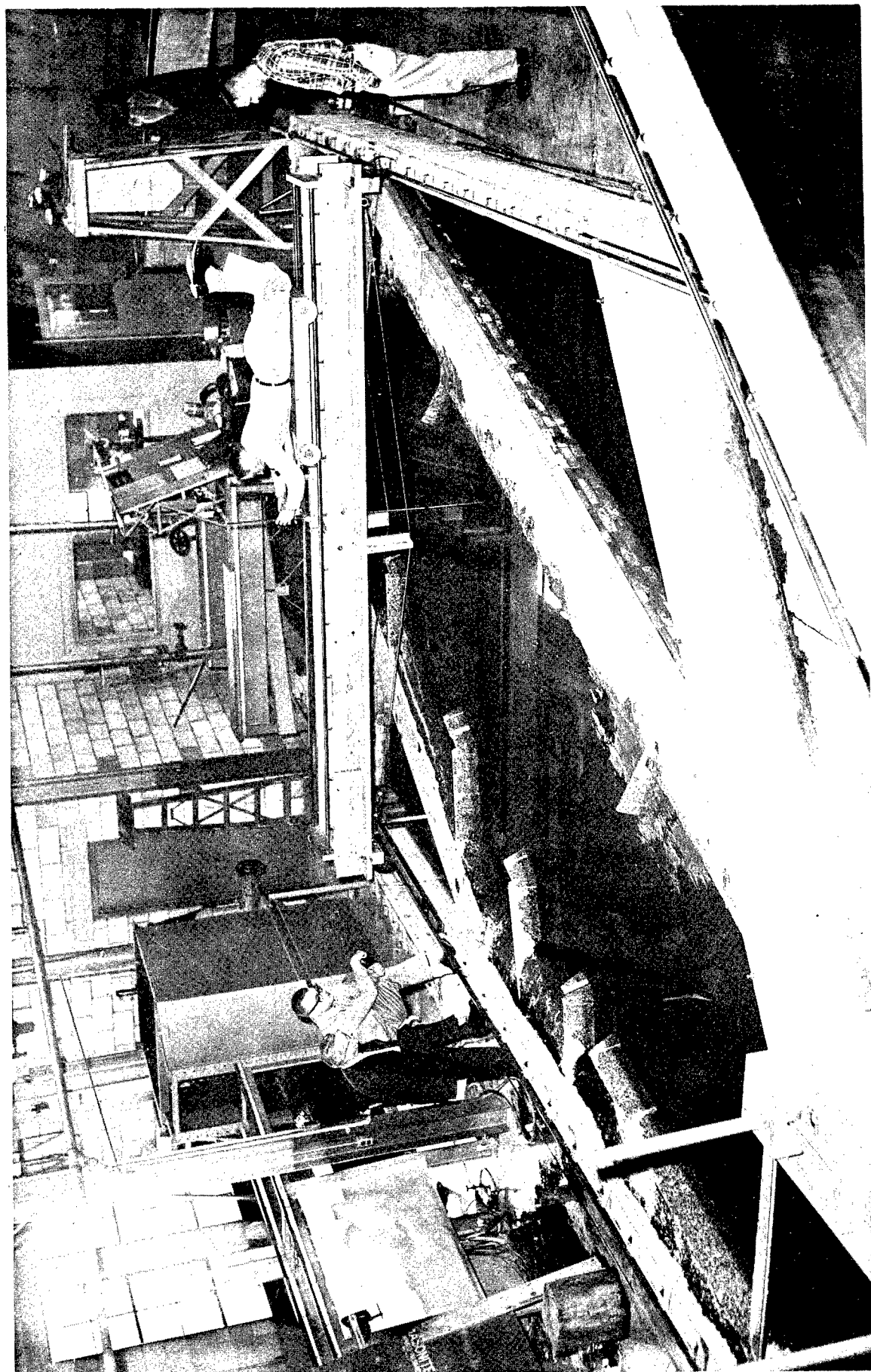
   a. Flume and Model Layout.

         The laboratory flume consisted of the following general integral
parts listed in the order of flow operation.A large sump under the floor contained
the water storage supply. Storage water was lifted by a hydraulic pump from the
sump to a small constant level reservoir located overhead. This reservoir was
a controlled source of water supply through a 12" pipe to the flume head tank
where the discharge was adjusted. Adjacent and downstream from the head tank
was a sediment supply elevator equipped with a rise speed control. The test
section or model area was just downstream from the sediment elevator. The tail
gate section containing a material weighing basket and an adjustable tail gate
assembly was located at the downstream end of the model section. A return
channel located under the floor connected the downstream side of the tail gate
with the large storage reservoir and completed the flow cycle. A pictorial view
of the head tank, model area and tail section is shown on Plate A. The original
flume dimensions of five-foot width by thirty-foot length were adjusted to 15-
foot width by thirty-foot length to better allow for the large width – depth
ratio of the prototype. This permitted a model channel width of five feet, while
the curvature of the bend used the remaining width space. Temporary interior
walls were placed within the extended flume to reduce the amount of bed material
required for modeling the channel area. Plate II shows the section of the river
as modeled in the flume.

   b. Model Materials.
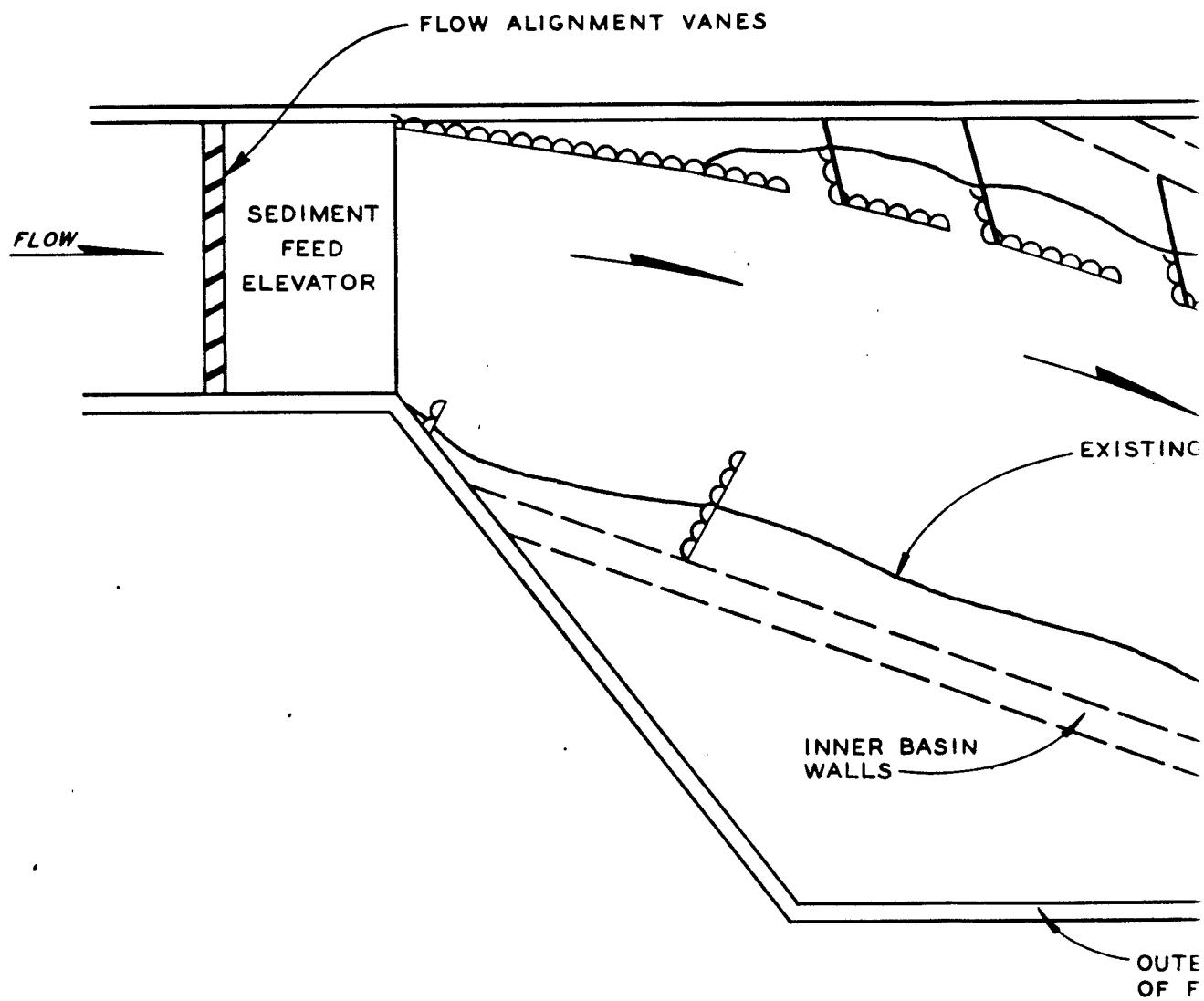
   (1) Movable Bed Material.

         During the investigation preparation phase, it was decided that
similarity of sediment transport between model and prototype could best be obtained
by the use of a low density material for the movable bed. A search was made for
a material which would be readily available and reasonable in cost. Various
plastics were considered, but the cost of the quantity needed prohibited their use.
Through contacts with Professor Ralph R. Marlette, of the Department of Civil
Engineering at the University of Nebraska, it was learned that finely ground walnut
shells could possibly be used. Further investigation revealed that this material
was readily available commercially in gradations between the No. 6 sieve and the
No. 100 sieve. This material is commercially prepared for use as an abrasive
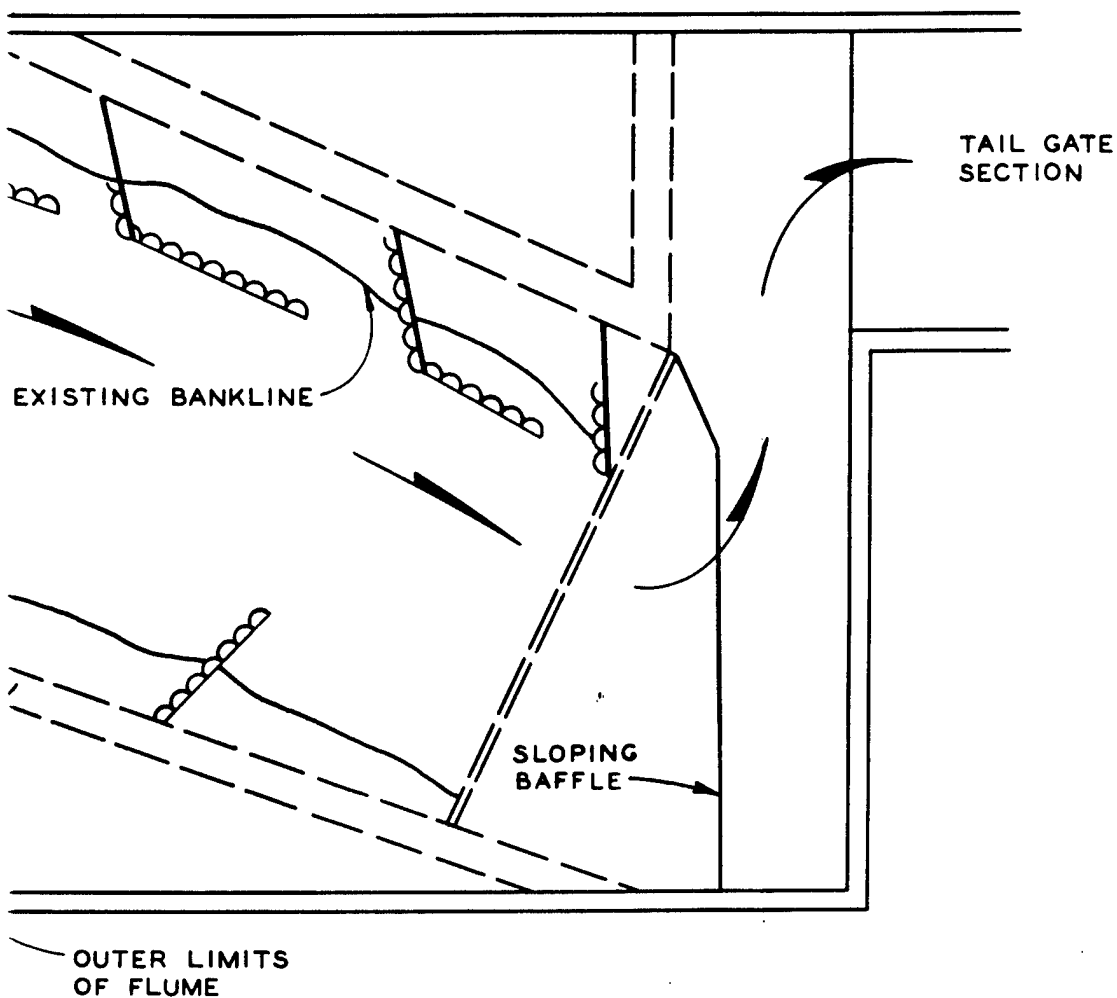agent for sand blasting where the use of a harder material would cause damage.

         Samples of both black walnut and english walnut shells were
obtained and tested for gradation and specific gravity. The specific gravity
ranged from 1.309 for the black walnut shells to 1.325 for the english walnuts.
This value is not a true specific gravity but more nearly represents the specific
weight of the material under water. In making a specific gravity determination,
it was found that the walnut shells could not be dried to a constant weight.
Therefore, the specific gravity was determined with the material in a saturated
surface dry condition. The black walnut shells had objectionable amounts of
extremely fine material and were rejected for that reason. Five tons of the
ground english walnut shells were obtained for use in the model. The commercial
specifications for the material indicated less than 4% should be retained on the
No. 40 sieve and less than 4% should pass the No. 140 sieve. Mechanical analysis
of the material in a dry state showed the medium size to be approximately 0.30 mm.

General view of model in operation with a typical structure layout in the flume

PLATE A

FLOW ALIGNMENT VANES

FLOW

SEDIMENT
FEED
ELEVATOR

EXISTING

INNER BASIN
WALLS

OUTE
OF F

①

TAIL GATE
SECTION

EXISTING BANKLINE

SLOPING
BAFFLE

OUTER LIMITS
OF FLUME

MISSOURI RIVER DESIGN STUDY
STUDY REACH AT TOBACCO BEND
U.S. ARMY ENGINEER DISTRICT, OMAHA
CORPS OF ENGINEERS OMAHA, NEBRASKA
MAY · 1964

②

PLATE II

Samples of the material were periodically taken from the flume throughout the duration of the test to determine if the physical properties were remaining relatively constant. The samples were tested for specific gravity, mechanical analysis, and visual accumulation analysis. From the start it was evident that the volume of the material increased slightly when it was saturated. The extent of this volume change was determined by sieving the samples in both the wet and dry condition. The results of the mechanical analysis are shown on Plate III. These curves indicate the ground walnut shells increase in size about 10 percent when saturated. Plate III also presents the mechanical analysis for Missouri River sand in the vicinity of the study reach. The similarity of the material to sand is illustrated on Plate B, which shows photomicrographs of both the ground walnut shells and Missouri River bed sand.

Operation of the model immediately indicated the performance of the ground walnut shells as bed material was highly satisfactory. The material looked, felt and performed like a light weight sand. Low velocities actively transported the material along the bed, and turbulence entrained and carried it in suspension. It was thus possible to observe areas of deposition as well as scour. It also exhibited a certain amount of cohesiveness and thus simulated bank caving in the prototype. Unexpectedly, the sensitiveness of the material to the rate of feed made it possible to observe the several bed forms and flow regimes that are known to exist in the prototype. Figure 1 on Plate C illustrates the rough bed that is associated with moderate depths, low velocity and a normal sediment supply. Figure 2 on the same plate shows the smooth bed that is associated with shallow depths, high velocity and an over supply of sediment. In both cases the overall roughness is probably the same. The use of the ground walnut shells also permitted a considerable reduction in the time required to complete a test run. In general a period of about 4 hours was required to obtain equilibrium conditions in the model. Had sand been used, the time to reach equilibrium would undoubtably have been much longer.

The ground walnut shells do have some objectionable features, however, they are not particularly serious. They do have a slight musty odor when wet and, if allowed to remain submerged without disturbance, produce fungus growths which have a very objectionable odor when exposed. The walnut shells also discolor the water quite rapidly, but this can be overcome by frequent changes of water. How long the material can be used without rotting or decomposing is not known. No decomposition was observed during the $2\frac{1}{2}$ month period of this investigation. Professor Marlette has used a small quantity of walnut shells periodically for about 3 years with no apparent change in characteristics other than a darkening in color. It is felt that the material can be used successfully for a fairly long period if it is dried between periods of use.

Operation of the model indicated the advantages of a system in which the bed material, passing through the model, would be recirculated with the water. The material which did not settle out in the model area or afterbay of the flume was transported over the tail gate and deposited in the return channel and storage sump from which it was very difficult to recover. The material that did deposit in the afterbay had to be manually transported back to the feed elevator. A uniform feed rate was also difficult to establish as the flow did not always remove the material uniformly from the surface of the sediment elevator. A recirculating system would alleviate these problems as it recycles the sediment and automatically establishes equilibrium conditions.

(2) Structure Materials.

After the preliminary tests on the bed material were completed, additional tests were conducted to develop model structures. Actual river dikes are constructed of a mass of rock with a rough surface boundary, therefore, some roughness was also desirable in the model. Due to the distortion between the horizontal and vertical scales, it was determined that the use of actual rock for modeling was undesirable because it developed excessively flat structure side slopes. Various other materials were also tried, such as, glass screen, wire lath, concrete, smooth sheet metal and sheet metal with various rough surfaces. Sheet metal with small stones attached appeared to give the best results of those examined. The sheet metal also adapted itself to model changes by using an interlocking "S" connector available locally. A typical end section of a dike, the "S" connector, and roughened structure is shown in Plate D.

c. Instrumentation.

Detailed measurements were made of both the hydraulic and dimensional characteristics during and after each test run. The discharge was determined at regular intervals during each test by measuring the differential pressure across an orifice in the supply line with a water manometer. Velocity measurements were made with a pygmy current meter and with surface floats. Confetti was also used to observe the surface flow patterns. Water surface and bed elevations were measured with a point gage from a large movable bridge (See Plate A), which completely spanned the flume. Steel rails mounted on both walls of the flume supported the bridge, and another set of rails on the bridge supported the movable carraige for the point gage. Vertical deflections in the bridge were kept to a minimum by constructing it of heavy lumber and stiffening it with tension cables on the bottom side. Water surface profiles were obtained from measurements at the same location in the flume for each test run. Before each test run the point gage was zeroed at each measurement location with a Dumpy level or by a reading on still water. This was done to minimize small errors due to bridge deflection and unevenness in the rails and carriage wheels. Water temperature and scour hole dimensions were also recorded for each test.
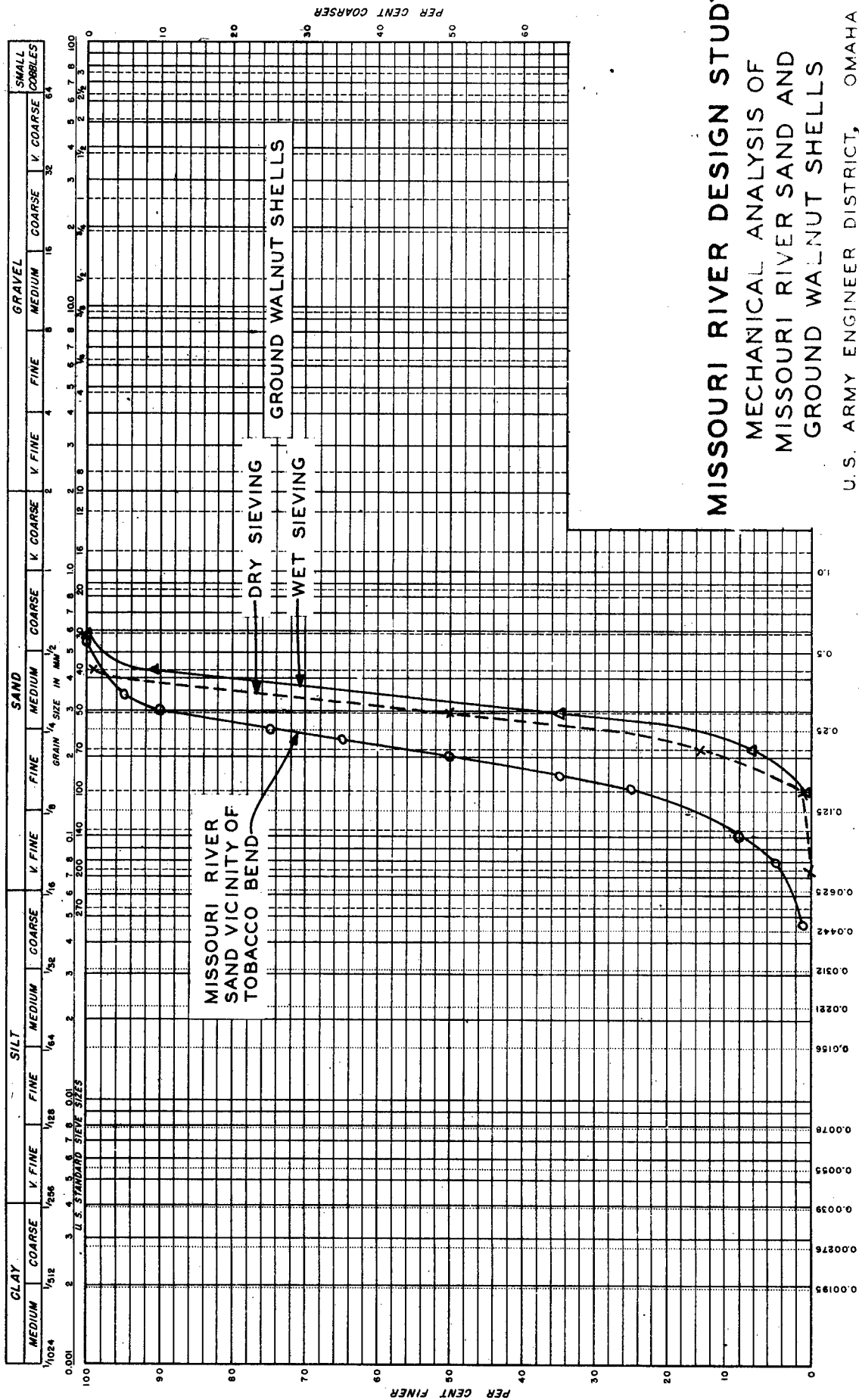
Considerable difficulty was experienced in maintaining the bed in its final form while dewatering the flume after a test run. A method of using a submerged light to determine the bed elevation with the water remaining in the flume was tried, but the discoloration of the water made this impractical.

The sediment supply to the system was controlled by a variable speed elevator located at the entrance to the flume. However, as previously discussed, there was some difficulty in maintaining a uniform feed rate of bed material. No attempt was made to measure the rate at which sediment was transported through the model channel.

d. Preliminary Testing.

In order to obtain a familiarity with the bed material and develop basic operational techniques, a series of preliminary tests were conducted. During these tests the entrance and exit conditions to the model area

MISSOURI RIVER DESIGN STUDY

MECHANICAL ANALYSIS OF
MISSOURI RIVER SAND AND
GROUND WALNUT SHELLS

U.S. ARMY ENGINEER DISTRICT, OMAHA
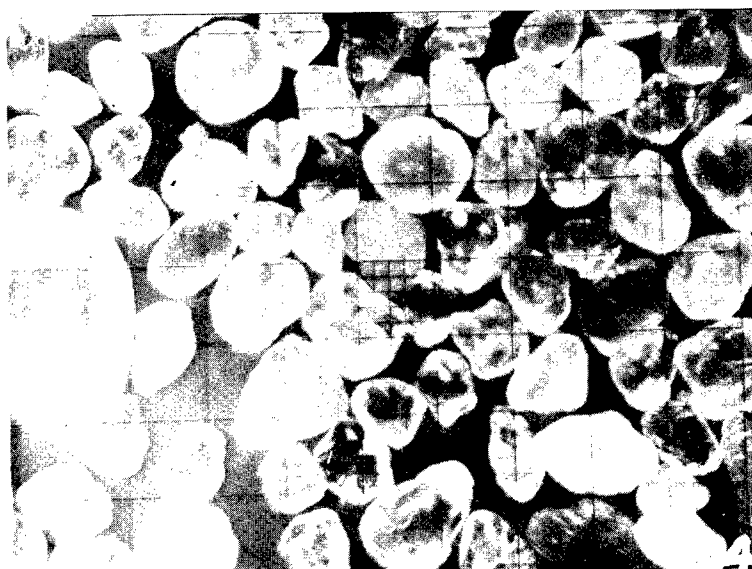CORPS OF ENGINEERS OMAHA, NEBRASKA
MAY 1964

GROUND WALNUT SHELLS

DRY SIEVING

WET SIEVING

MISSOURI RIVER
SAND VICINITY OF
TOBACCO BEND

AMERICAN GEOPHYSICAL UNION GRADE SCALE

PLATE III

Fig. 1   Missouri River Bed Sand Grid Size:
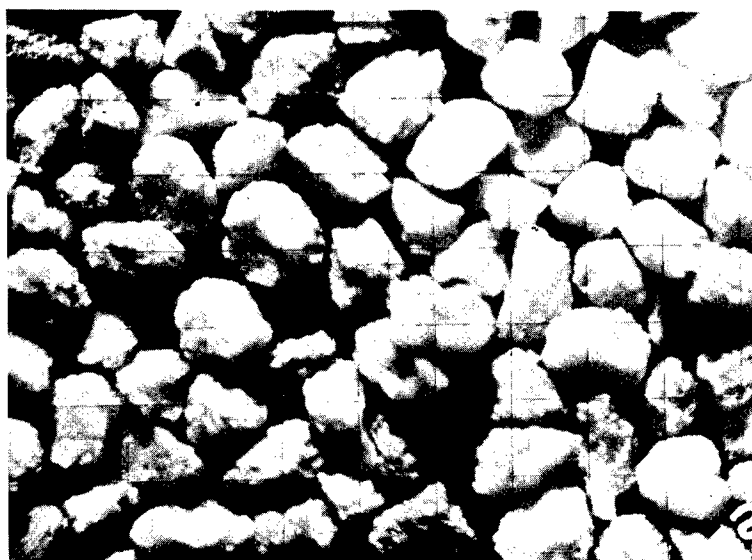0.39 mm

Fig. 2   Ground Walnut Shells Grid Size:
0.39 mm

PLATE B

Fig. 1   Typical rough bed associated with normal depths, velocities
         and feed rate

Fig. 2   Smooth bed associated with shallow depths, high velocities
         and high feed rates

Variation in bed forms obtainable with ground walnut shell bed material
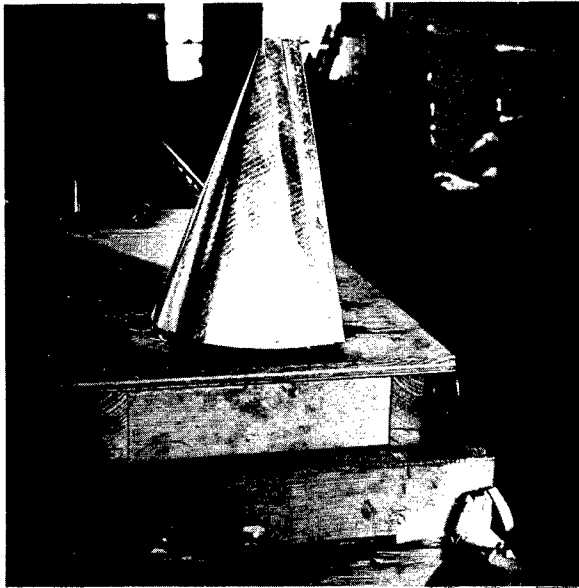
PLATE C

Fig. 1 "L-head" structure
end section prior to being
covered with small crushed
stone

Fig. 2 "L-head" structure end
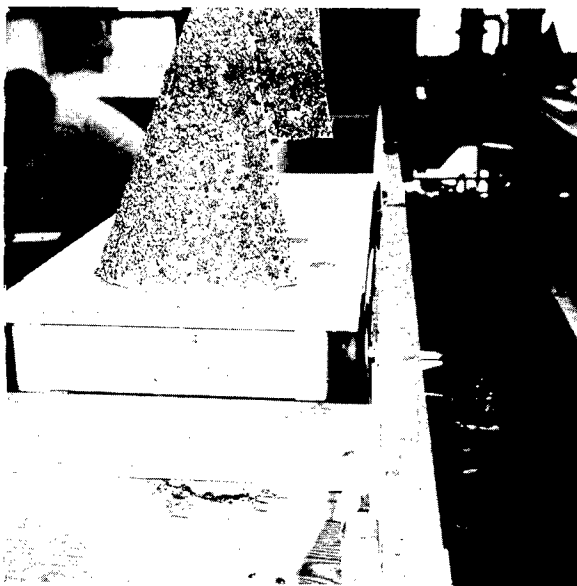section showing the "S" shaped
connector

Fig. 3 "L-head" structure with
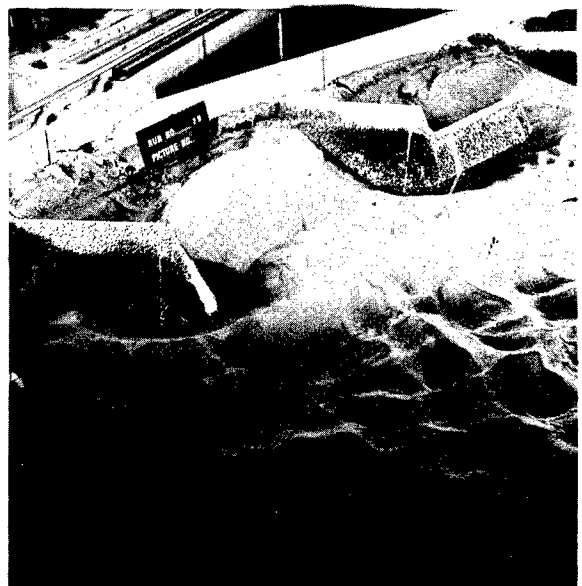the crushed stone applied to
surface for structure roughness

Fig. 4 Typical view showing
structure placement within
model area

PLATE D

were modified because of the flume arrangement. A series of deflection vanes were constructed near the entrance of the flume to simulate upstream entraining conditions. A sloping baffle was constructed at the downstream section to maintain flow through the model area parallel to the channel center-line because of the location of the tail gate section to the end of the model area. (See Plate II).

Sediment elevator speeds which induced sediment transport rates were studied in relation to various flow discharges to determine material reactions and limitations in development of bed dune patterns which could be satisfactorily considered relative to the patterns in the prototype. These studies provided for the selection of a specific discharge, sediment feed rate and water surface elevation to be used during the investigation testing.

A general outline of the operational procedure developed is as follows:

(1) Control structures were constructed in the model test area and the bed was shaped to an established cross-section.

(2) Sediment elevator was filled with bed material and surface shaped to promote uniform feeding at start of test.

(3) Pumps were started and model was slowly flooded from the downstream end. This back-flooding prevented the initial flow from cutting into the shaped bed.

(4) Point gage on bridge was zeroed with a Dumpy level during back-flooding.

(5) Water surface was allowed to rise higher than desired during flooding to provide cohesion of the bank areas to be later exposed. The tail gate was then slowly lowered as the discharge valve was opened. This adjusting continued until the selected water surface elevation and discharge rate were obtained.

(6) When water surface and discharge were established, the time was recorded and the sediment elevator was started up at the desired rate.

(7) The following measurements were made during the test run:

(a) Water surface elevations were taken every half hour in conjunction with discharge check readings.

(b) Water temperature and elevator travel was periodically recorded.

(c) Discharge measurements and water surface velocities were obtained.

(8) At the completion of each run, the tail gate was raised as the discharge was reduced to keep the water in the model area. This was done to prevent a fast runoff which disturbs the bed formation.

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(9) Dewatering of the model area was then accomplished very slowly as the material was very sensitive to any flow.

(10) Upon completion of dewatering, the bed area was cross-sectioned, dike scour holes measured and photographs were taken.

6. Investigation Testing.

    a. Testing Condition Concepts.

Preliminary testing provided data to establish certain variables as constants during structure testing, such as, discharge, water surface elevation, and sediment transport rate, all of which influence the effects of control structures on the channel section shape. By fixing these important variables, testing could proceed for the resulting physical changes produced in the model bed would vary in relation to each structure arrangement.

Existing structure systems in the prototype varied in their individual arrangement and curvature between bends. Areas controlled by open systems of spur dikes also varied in dike spacing and location within an overall bend. With this in mind, it was apparent that several concepts in studying the problem could be used and are summarized as follows:

(1) Testing a series of L-head lengths based on assuming the effectiveness of an L-head extension as a function of the remaining gap or opening between the extension and the next downstream structure. Thus if the spur dike spacings were variable, the length of the L-head extension would also vary but the remaining openings would be of equal size throughout the study area.

(2) The opposite approach from (1) can also be a test possibility, where the length effectiveness of the L-head may be a function only of the length of an individual extension and not dependent on the gap. This would result in all the L-head extensions being equal in length and the opening or remaining gap would be variable.

(3) Another concept to study the length effectiveness could be based on an accumulative effect where each total opening between spur dikes would be closed by L-head extensions based on a percentage of gap closure. Under this condition, both the L-head and remaining opening would be variable length within the structure system.

Each of the above concepts had the possibility of a two dimensional adjustment in testing (length and height). Thus, an infinite number of structure arrangements become possible if both length and height studies are conducted concurrently. The limited period during which the laboratory was available required adopting a test schedule which would first study the length problem with exposed L-head structures. Results of the length testing would be used to indicate the most desirable lengths for investigating the height portion of the problem.

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By controlling the discharge and sediment transport, the model bed elevation can be adjusted by altering the water surface elevation. This capability simplified the structure height investigation by allowing a change in water surface elevation to impose a change in the structure elevation studied.

In the preparation for each test run the model bed was reshaped to an established form which required bed aggradation during the initial portion of the test run. Bed aggradation continued until the system established equilibrium. Equilibrium is defined as a condition where the rate at which sediment is being deposited is equal to the rate at which scour occurs or material is being picked up. Thus, the section is neither in a state of aggradation of degradation. Bed reshaping provided good laboratory test controls and simplified test structure adjustments but required extension of the test run period to insure that the model area had established a condition of equilibrium.

b. Investigation Test Series.

(1) Test Series No. 1.

The first series of tests was conducted on the assumption that the total effectiveness of the dike extension is a function of the gap or space between the dikes. The amount of opening was based on a percentage of the channel width; however, since only one channel width was analyzed, no direct comparisons with other channel widths are possible. The variable dike spacing placed a limitation on this approach, with the distance between the closest two spur dikes being the maximum gap possible around any particular bend. (See Plate IV)

In order to establish the effectiveness of the difference lengths studied, base tests were conducted with no L-head extensions and also with the entire concave side completely screened with revetment. These tests established the extreme conditions, and the results of any given intermediate condition can be compared with them.

The discharge, sediment feed rate and water surface elevation were held constant throughout the tests. The following tests were made in this series.

    Run 8 0 = Complete Revetment
    Run 15 0 = Complete Revetment
    Run 9 Gap equal to 15% of Channel Width
    Run 10 Gap equal to 20% of Channel Width
    Run 11 Gap equal to 32% to Channel Width
    Run 12 Gap equal to 40% of Channel Width
    Run 13 Gap equal to 48% of Channel Width
    Run 14 Gap equal to 55% of Channel Width
    Run 7 100% = No L Extensions
    Run 5 100% = No L Extensions

A summary of the data obtained from this series of tests appears in Table 2. Photographs taken at the completion of each run appear in Plate E.

(2) Test Series No. 2.

The second series of tests were also conducted to study the most effective length of the L extensions. In this series, the length of extension was set by a percentage of the gap or opening. Since the distance between spur dikes was variable around the bend, the length of L and the opening is also a variable between each spur dike. Construction techniques with the model materials limited the minimum study length to 21% of the distance on Dike No. 1, therefore 21% of the distance was also used on the remaining spur dikes. (See Plate IV)

Discharge, sediment feed rate, and the water surface elevation were held to the same values used in test series No. 1. The following tests were performed in this series.

Run No. 17 - 21% of gap enclosed by L-head extensions
Run No. 18 - 40% of gap enclosed by L-head extensions
Run No. 19 - 63% of gap enclosed by L-head extensions
Run No. 21 - 50% of gap enclosed by L-head extensions
Run No. 22 - 80% of gap enclosed by L-head extensions

The test runs of the extreme conditions also apply as base runs for comparative analysis in this test series. These base runs were test No. 8 and No. 15 with complete revetment along the concave bank and test No. 5 and No. 7 with open spur dikes (no L-head extensions).

The accumulation of data obtained from this series of tests appears in Table 2 and comparative photographs taken following each test are shown on Plate F.

(3) Test Series No. 3.

The third series of tests began the study of the most economical height to which the L-head dikes should be constructed. For these tests, the spur dikes were placed equal distance apart around the bend to eliminate the dike spacing variable. The L-head extensions were constructed to a length of 70% of the distance between the spur dikes and held constant at this length while varying the height. The relative effect of the various heights can then be compared. The discharge and sediment feed rate were held to the values used in previous tests. As previously stated in the preliminary testing paragraph, the water surface was adjusted to study the various structure heights. The following tests were performed in this series:

Run No. 23 - Top of L-head extension 1' below water surface
Run No. 24 - Top of L-head extension 3' below water surface
Run No. 25 - Top of L-head extension 6' below water surface
Run No. 26 - Top of L-head extension 9' below water surface

Laboratory data for these tests appears in Table 2 and comparative photographs are shown on Plate G.
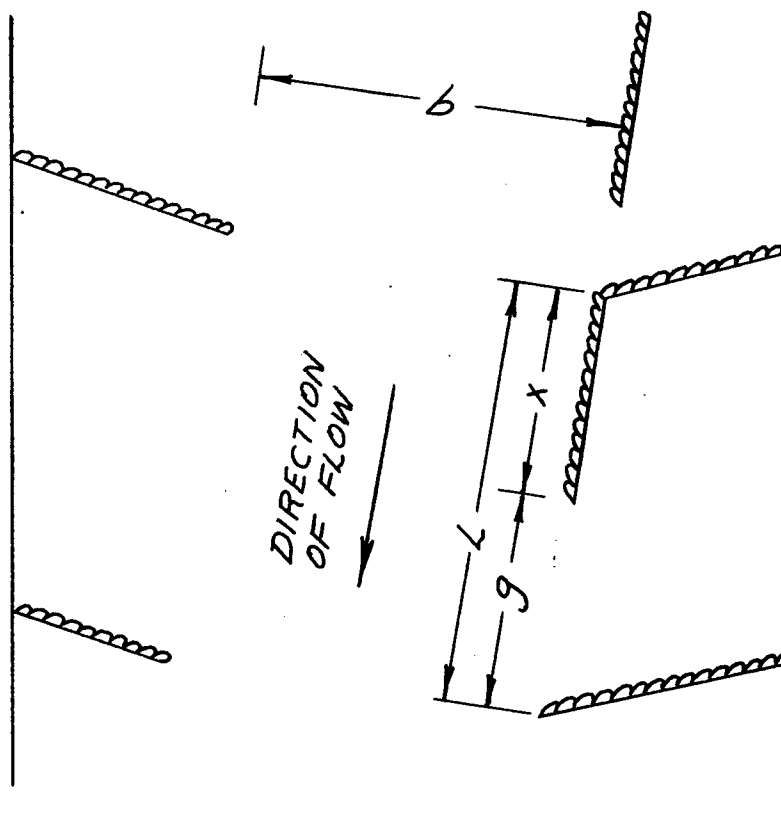
Test Series No. 1.   The length of the opening, g, is a function
    of the distance b or g = (f) b

Test Series No. 2.   The length of the L-head extension is a
    function of the total distance between the spur dikes or
    x = f (L).

    Where
        b = effective width of the channel
        L = distance between spur dikes
        x = length of L-head extensions
        g = length of opening or gap between the
            downstream end of the L-head and the
            next downstream spur dike

TEST SERIES LAYOUT SKETCH

PLATE   IV

Fig. 1   Base test run with a
continuous revetment along
designed curve

Fig. 2   Opening equal to 15%
channel width

Fig

Fig. 5   Opening equal to 40%
channel width

Fig. 6   Opening equal to 48%
channel width

Fig

Test Series No. 1

Conducted on the assumption that the total effectiveness of the L-head extensions is a
space left between the extension and the next downstream dike terminal. The amount of
percentage of the channel width.

①

Fig. 3   Opening equal to 20%
          channel width

Fig. 4   Opening equal to 32%
          channel width

Fig. 7   Opening equal to 55%
          channel width

Fig. 8   Base test with spur
          dikes only

extensions is a function of the gap or
. The amount of opening was based on a

②   PLATE E

Fig. 1   Base test run with a
continuous revetment along
designed curve

Fig. 2   Opening 20% and L-head
80% of each individual space

Fig. 5   Opening 60% and L-head
40% of each individual space

Fig. 6   Opening 79% and L-head
21% on each individual space

①

Fig. 3   Opening 37% and L-head
         63% of each individual space

Fig. 4   Opening and L-head 50%
         of each individual space

Fig. 7   Base test with spur
         dikes only

Test Series No. 2

Conducted on the assumption that
the total effectiveness of the
L-head extensions is a function
of amount of closure of each
individual space between spur
dikes. Since the distance
between spur dikes is variable,
the length of L-head extension
and the downstream opening
varies between each spur dike
within each test run.

ⓐ

Fig. 1   Top of L-Head
      1' below water surface
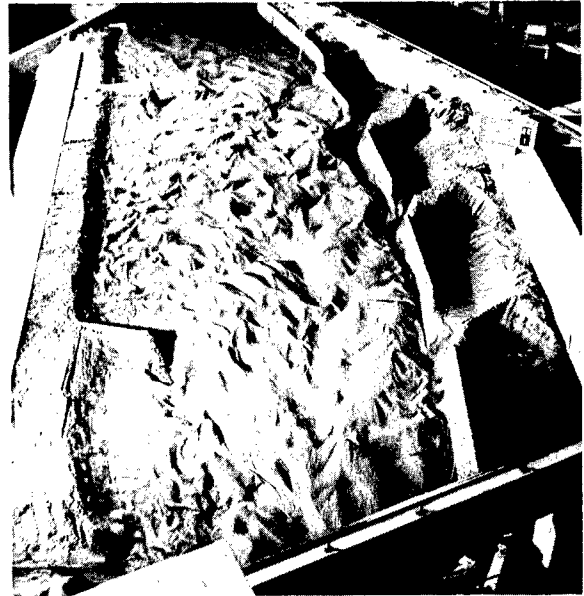

Fig. 2   Top of L-Head
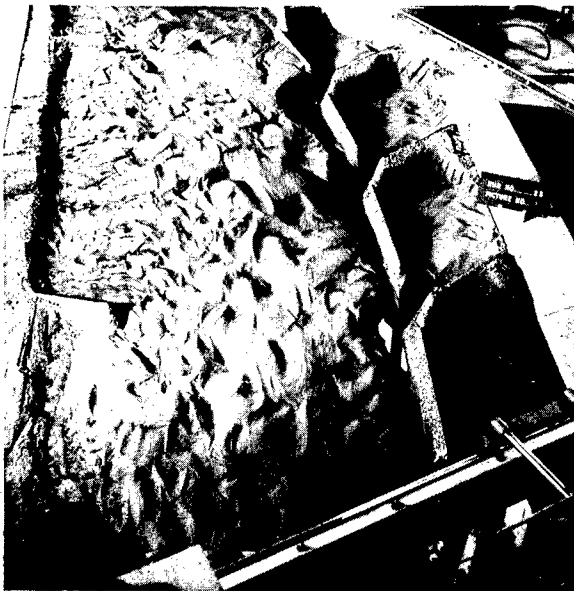   3' below water surface

Fig. 3   Top of L-Head
      6' below water surface

Fig. 4   Top of L-Head
      9' below water surface

SERIES NO. 3.   This series of tests was performed to determine the most
        efficient height of the L-Head structures. The length was
        held constant at 70% of the distance between the spur dikes,
        and the height varied from 1' to 9' below the water surface.

PLATE G

(4) Test Series No. 4.

The fourth test series was a continuation of test series No. 3; however, the length of the L-head extension was changed to 50% of the distance between the spur dikes. The following tests were performed in this series.

Run No. 27 - Top of L-head extension 2' below water surface
Run No. 28 - Top of L-head extension 4' below water surface

Laboratory data for these tests is shown in Table 2.

7. Analysis of Laboratory Data. The study development of the laboratory data is composed of hydraulic computations, hydrographic investigations and general observations (noted during testing).

a. Hydraulic and Hydrographic Analysis.

(1) Channel Cross-section. At the close of each test run, a series of channel cross-sections were obtained at positions along the flume which would provide a good representation of the bed configuration. A horizontal increment of 0.2 feet was used along the section between points to obtain an accurate shape of the section and provide data which could be easily utilized in quickly developing an average sectional area. Using the individual cross-sections and the point relation to the distance from the concave alignment, three composite or accumulative channel sections were developed. First, a minimum sectional area was computed using the minimum depth obtained at each specific distance from the concave alignment. Second, an average section was computed in a similar manner using the average depths along the alignment. The third, a maximum section was computed using the greatest depths along the line of cross-section points which were equal distance from the concave alignment. The results of these computations are listed on Table 2.

(2) Average Velocity. The average velocity for each individual test was computed by determining the average discharge during the test period and dividing this discharge by the average cross-sectional area as described above. (Computation results listed on Table 2.)

(3) Hydraulic Radius. For channels with a wide shallow cross-section, the hydraulic radius is approximately equal to the average depth. In later computations the average depth shown on Table 2 was used in lieu of a computed hydraulic radius.

(4) Water Surface Slope. It appeared from a general comparison of the water surface profiles that the entrance and exit conditions in the flume influenced the adjacent water surface readings; therefore, the extreme end points were omitted from the slope determination. The remaining points were plotted and the least squares method was applied to arrive at the final water surface slopes, listed on Table 2. The slope of the energy gradient was assumed to be parallel with the final water surface slope.

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(5) Manning's "n" Value. Using the above computed hydraulic data, Manning's friction factor, "n", was computed using the following formula:

$$n = \frac{1.486 \, AR^{2/3} S^{1/2}}{Q}$$

Where n = Manning's friction factor, A = average cross-sectional area, R = hydraulic radius, S = water surface slope, and Q = average discharge. This factor which is a measure of the composite roughness (bed configuration and boundary irregularities) is listed on Table 2.

(6) Roughness and Shear Intensity. Using the formulas presented in the paragraph on hydraulic considerations, the bed material specific gravity of 1.33, and the grain sizes from the mechanical analysis determined by wet sieving, the following values were computed and listed for comparative purposes on Table 2.

R' = measure of hydraulic roughness due to grains that form the bed
R" = measure of the roughness from dunes, bars and other boundary roughness
R'/R_T = ratio of hydraulic radius due to bed grains to total hydraulic radius
ψ' = intensity on shear on the bed

(7) Bed Roughness. A special bed roughness analysis was developed and adapted to the electronic computer. The basic concept of the analysis measured the amount that individual bed elevations deviated from the computed average bed elevation. This could be defined as a Standard Deviation Analysis and was based on the following formula:

$$S_x = \left(\frac{\Sigma x^2}{N-1}\right)^{\frac{1}{2}}$$

Where S_x = Standard deviation

x = Difference from the mean

N = number of points

The numerical value of S_x (computer output data) was a comparative indicator of bed roughness between tests. An increase in the S_x value reflected an increase in bed roughness.

The graph shown on Plate V was developed from the above statistical analysis and shows the relationship between the standard deviation from the mean depth and the percent of the distance inclosed by L-head dike extensions. The standard deviation from a mean value becomes a measure of the amount of variation that exists between the measured points. It is possible for two sets of data to reveal identical mean values; however, the variation that existed in the basic points might vary considerably. This variation in depths is important in a navigable stream since the smaller variations result in more unobstructed flow area. The graph shows that the deviations are greatest and remain so until approximately 40% of the distance is enclosed by L-Heads, after which the deviation from the mean depth begins to decrease. The minimum amount of deviation was recorded when complete revetment existed around the concave side of the bend.

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Test Series No.	Run No.	Dike Exposure Percent	Average Discharge cfs	Average Flow Area ft^2	Average Depth $= R_T$ ft	Average Velocity ft/sec	Water Surface Slope ft/ft	R
1	15	0	0.820	1.105	0.215	0.742	0.000521	0.1
	8	0	0.825	1.2098	0.235	0.682	0.000866	0.0
	9	18.2	0.842	1.1020	0.220	0.764	0.000858	0.0
	10	29.1	0.820	1.1029	0.215	0.743	0.000772	0.0
	11	38.8	0.820	1.3661	0.266	0.600	0.001242	0.0
	12	48.5	0.820	1.3176	0.248	0.622	0.000795	0.0
	13	58.3	0.825	1.3075	0.253	0.631	0.000708	0.0
	14	66.7	0.820	1.2443	0.242	0.659	0.000733	0.0
	7	100.0	0.820	1.3623	0.265	0.602	0.000939	0.0
	5	100.0	0.838	1.4308	0.277	0.585	0.00115	0.0
2	15	0	0.820	1.105	0.215	0.742	0.000521	0.1
	8	0	0.825	1.2098	0.235	0.682	0.000866	0.0
	22	20.0	0.825	1.2273	0.240	0.672	0.000761	0.0
	19	37.1	0.827	1.3272	0.260	0.623	0.000705	0.0
	21	50.0	0.815	1.2276	0.237	0.664	0.000787	0.0
	18	60.0	0.820	1.2829	0.249	0.639	0.000852	0.0
	17	76.0	0.815	1.1615	0.226	0.702	0.000553	0.0
	7	100.0	0.820	1.3623	0.265	0.602	0.000939	0.0
	5	100.0	0.838	1.4308	0.277	0.585	0.00115	0.0
3	23	34.8	0.825	1.1945	0.232	0.691	0.000662	0.0
	24	44.4	0.825	1.3120	0.256	0.628	0.00109	0.0
	25	58.8	0.820	1.2562	0.244	0.653	0.000792	0.0
	26	73.2	0.820	1.2180	0.237	0.673	0.000536	0.0
4	27	56.8	0.823	1.2660	0.245	0.650	0.000835	0.0
	28	64.0	0.823	1.2035	0.233	0.684	0.000895	0.0

OGRAPHIC DATA

R'	R"	$\frac{R'}{\overline{R}_T}$	ψ	Manning "n" Value	Accum. X-Sectional Area Using:		
					Min. Point Depth	Av. Point Depth	Max. Point Depth
0.108	0.107	0.503	5.63	0.0164	C.8582	1.1050	1.3046
0.0635	0.171	0.270	5.68	0.0243	0.9444	1.2098	1.3736
0.075	0.145	C.341	4.76	0.0207	0.8813	1.1309	1.3820
0.078	0.137	0.363	5.11	0.0198	0.7820	1.1029	1.6249
0.039	0.227	0.147	6.31	0.0359	0.9569	1.3661	2.0771
0.059	0.190	0.238	6.86	0.0264	0.9667	1.3176	1.6101
0.065	0.188	0.257	6.69	0.0250	0.9931	1.3075	1.6876
0.068	0.174	0.281	5.45	0.0236	0.9672	1.2440	1.5574
0.049	0.216	0.185	6.80	0.0310	0.9834	1.3623	1.8056
0.040	0.237	0.144	6.67	0.0366			
0.108	0.107	0.502	5.63	0.0164	0.8582	1.1050	1.3046
0.0635	0.171	0.270	5.68	0.0243	0.9444	1.2098	1.3736
0.068	0.172	0.283	6.01	0.0235	0.8916	1.2273	1.6532
0.064	0.196	0.246	6.81	0.0258	0.9792	1.3272	1.7741
0.065	0.172	0.274	6.08	0.02400	0.9507	1.2276	1.4646
0.058	0.191	0.233	6.33	0.0268	0.9641	1.2829	1.8104
0.093	0.133	0.412	5.37	0.0184	0.9523	1.1615	1.3731
0.049	0.216	0.185	6.80	0.0310	0.9834	1.3623	1.8056
0.040	0.237	0.144	6.67	0.0366			
0.079	0.152	0.341	6.26	0.0209	0.9047	1.1945	1.4827
0.049	0.206	0.191	6.22	0.0314	0.9240	1.3120	1.6941
0.064	0.180	0.262	6.21	0.0248	0.9078	1.2562	1.6882
0.089	0.147	0.376	6.49	0.01946	0.8455	1.2180	1.5662
0.060	0.185	0.245	6.19	0.0258	0.9814	1.2660	1.5910
0.062	0.171	0.266	5.61	0.0253	0.9546	1.2035	1.4379

②

TABLE 2

COMPLETE REVETMENT

o   DATA FROM TEST SERIES NO. 2

70   80   90   100
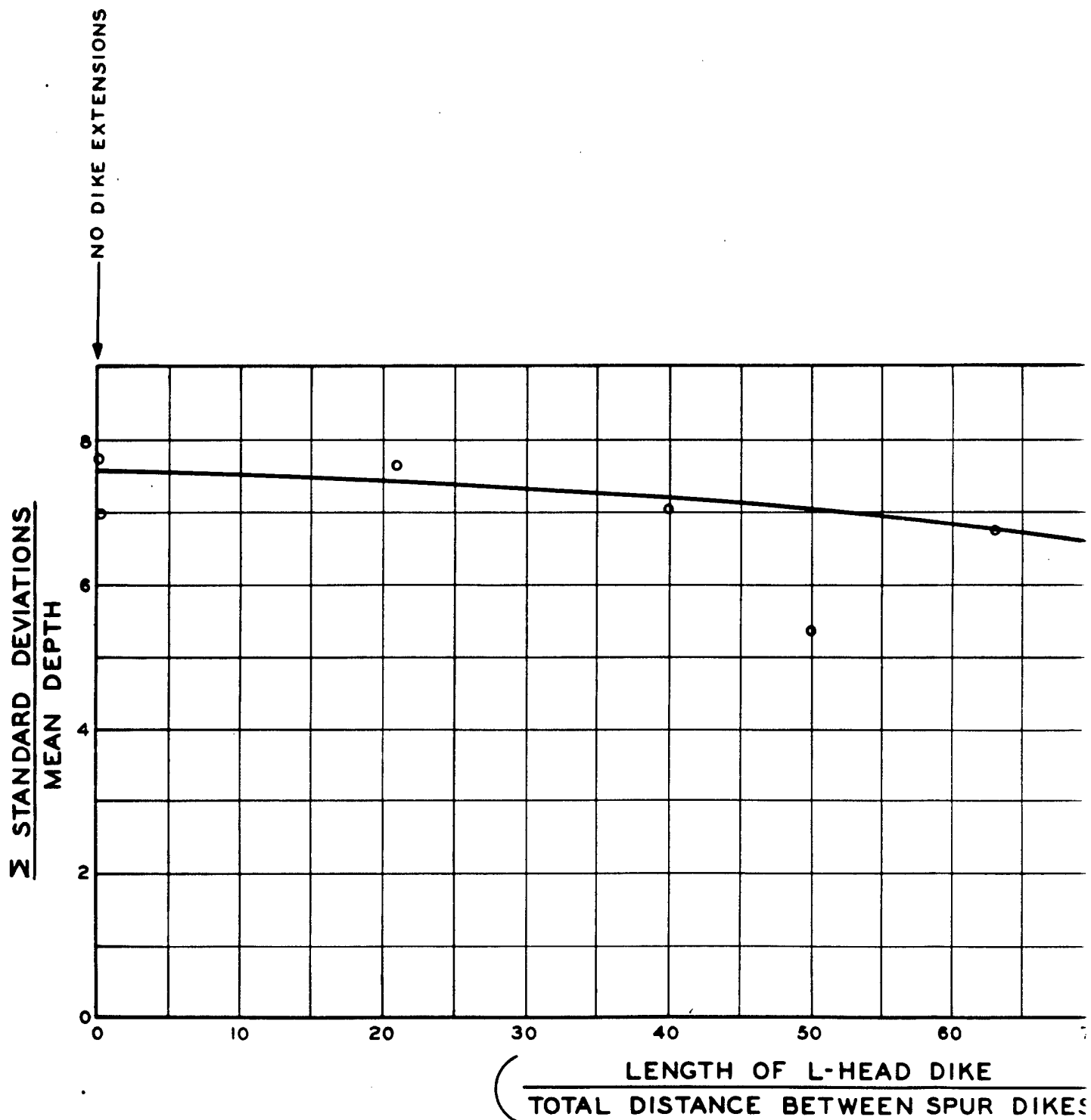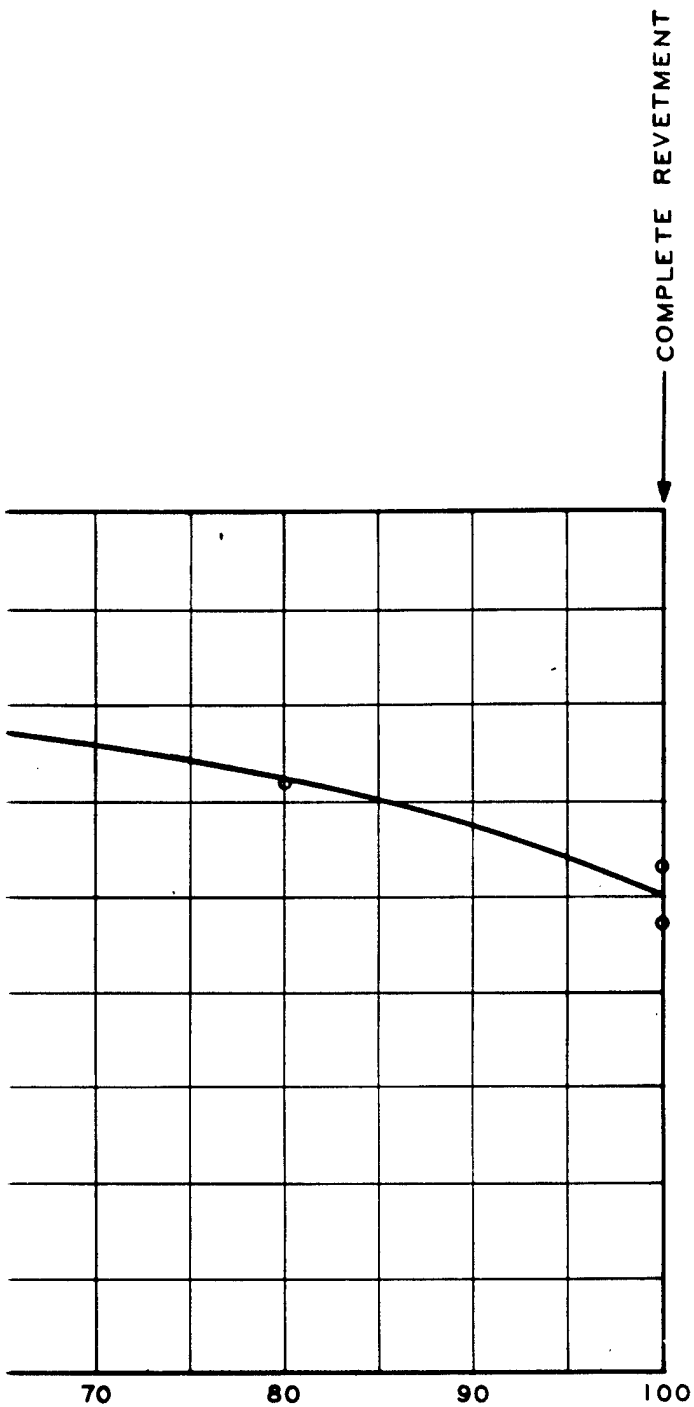
⎯⎯⎯
IKES) 100

MISSOURI RIVER DESIGN STUDY
STANDARD DEVIATION
VS.
LENGTH OF DIKE EXTENSIONS

U.S. ARMY ENGINEER DISTRICT,   OMAHA
CORPS OF ENGINEERS OMAHA, NEBRASKA
MAY 1964

②

PLATE V

(8) The graph on Plate VI shows the relationship that existed in test series 1 and 2 between the average water depth and the amount of exposed spur dike. The average depth for each test was divided by the average depth obtained in test run No. 7 (which was performed with no L-Head structures), thus providing a dimensionless ratio. The abscissa is a measure of the amount of spur dike that will be exposed to direct attack by moving water as it proceeds around a bend. The total possible exposure was determined using the assumption that the flow would expand on a 1 to 5 ratio from the end of the upstream structure. This exposure is therefore dependent on the length of the L-head and will vary from zero (complete revetment screening) to 100% (no L-Heads present). The use of this ratio allows correlation of the tests performed with unequally spaced spur dikes. The graph shows that the amount of scour is relatively constant between 0 and 50% exposure ratio. But beyond 50%, the average depth or scour increases rapidly, reaching the maximum value @ 100% exposure. The shape of the curve shows a definite break in the curve slope between 40 and 50% exposure.

This break in slope reflects that scour is greatly reduced by L-head extensions lengths up to 60% of the distance between spur dikes and that scour is not materially reduced as the L-head extension extends beyond the 60% length.

(9) The graph shown on Plate VII also illustrates the scour characteristics of the various L-head arrangements. Immediately after each test run, the dimensions of the scour holes which developed around the ends of the spur dikes were recorded. The amount of scour at this location is dependent on the degree of turbulence present at the ends of the spur dike, and therefore becomes a function of the length of the L-head. The distance that this action affects the bed upstream from the structure L_x is one measure of this turbulent action. The graph shows that the size of resulting scour hole increases as the length of the L-head decreases.

(10) The basic Manning equation includes all of the hydraulic variables necessary to determine the discharge. The value of "n" in this equation is a measure of the composite roughness of the channel. As the roughness increases, the value of "n" will also increase. The graph shown on Plate VIII illustrates how this roughness value changed as the length of L-head changed. The slope of the line is relatively constant between 0 and 50% exposure, but increases rapidly between 50 and 100% exposure, indicating that, on an incremental basis, the channel roughness can be reduced more when the initial segments of the L-head are constructed than when the final stages are constructed.
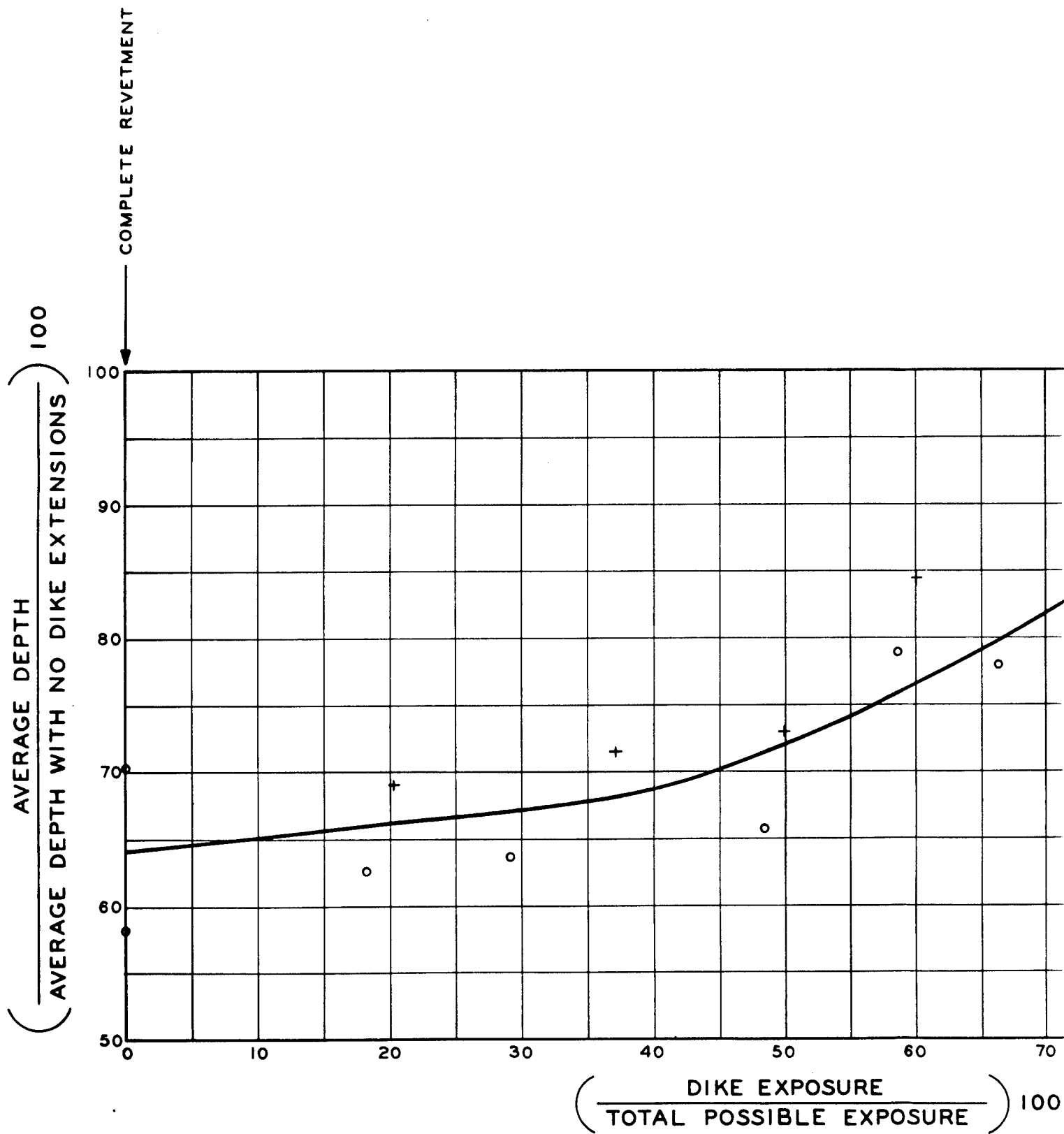
(11) The water surface slope also reacts to the general channel configuration. A smooth bed in a given reach of a river will have a flatter slope than a rough channel through the same reach. The graph on Plate IX shows the relationship that existed between the water surface slope and the lengths of L-head dike. The water surface slope was at a maximum when no L-heads were in place and decreased rapidly until about 50% of the spur dikes were exposed. Very little change in the slope was apparent when more than 50% of the distance was enclosed by spur dikes.
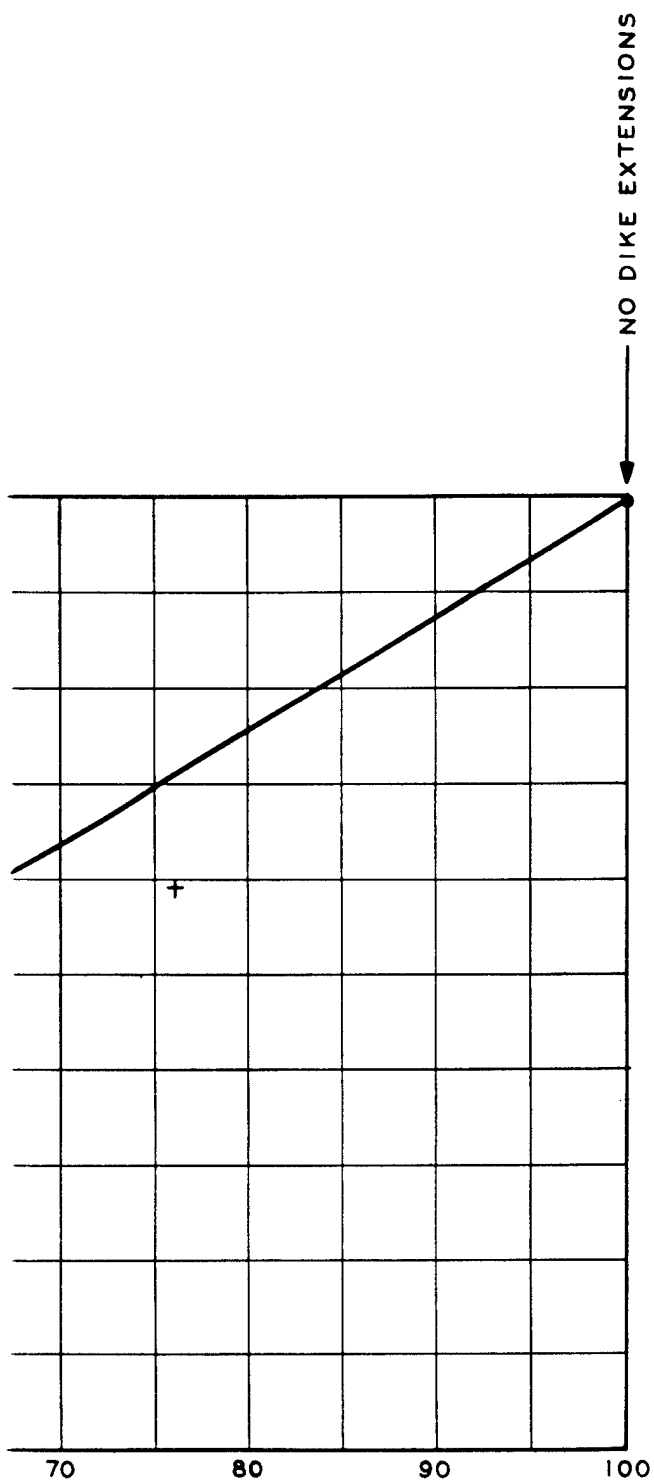
(12) The series of graphs on Plate X were developed in studying the physical change in the channel roughness for 60% of the model's channel width. The 60% channel section taken on the concave side was considered as the approximate navigation portion of the total channel. The graph in Figure 1 was derived from data obtained in "Test Series No. 1" and shows a bed roughness factor for equal gap openings plotted as a percent of the channel width. The second graph (Figure 2) was developed to show the bed roughness factor as it compared to a channel condition factor. The "channel condition factor" was derived by taking the minimum sectional area for 60 percent of the concave channel width and dividing that area by the total accumulative minimum channel area. This factor, a non-dimensional number, reflects only that as the factor approaches unity a more usable and efficient navigation channel exists. Figure 1 and 2 graphs can be used jointly as both have a common abscissa making it possible to read between charts using the common value of the roughness factor.

The graph in Figure 3 is a conversion graph which provides for transferring from a gap opening in percent of channel width to the total L-head extension length as a percentage of the total open area throughout the model test length. This conversion was used for developing the graph in Figure 4 and when data is converted provides indications on a similar base to those studies previously presented.
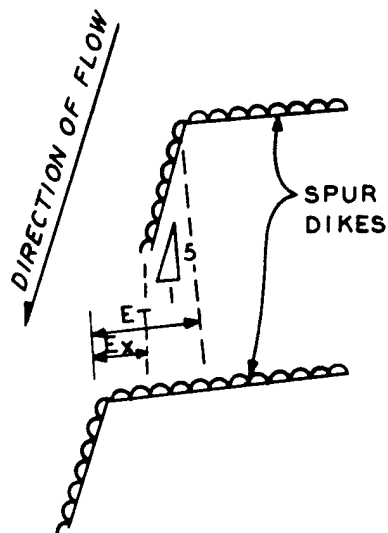
The bar graph (Figure 4) was plotted to present the rate of channel improvement as it related to the accumulative total lengths of L-head extensions. Increments of channel improvement were obtained by reading the roughness factor for a gap opening in Figure 1 and then using the same roughness factor, in Figure 2 read the value of channel improvement factor. The difference in the channel improvement factors for two readings provide an increment of change for the range of the corresponding gap openings. In developing the bar graph (Figure 4) readings were taken for each 2.5% of gap opening. The initial gap opening was converted using Figure 3 and the increment of channel change was then plotted on the bar graph over the range of total L-head extensions derived from the conversion graph. This resultant graph indicates the length at which the maximum rate of navigation channel improvement was attained in testing and ranges from 42 to 45 percent total accumulated L-head closing of the open spur dike area. The graph also indicates that the rate of improvement is greater for the initial 45% construction than for the remaining 55%. Also the rate of improvement is more rapid after 27% closing and decreases considerably after 67% closure of the total opening.

b. General Observations. Many articles have been written regarding the influence of sediment transport on the character of alluvial bed channels and their regime transformations. The ability of this bed material, because of its sensitivity to flow, to dramatize sedimentation influence was the most surprising benefit obtained from the investigation. By frequently changing the water, which became stained from the walnut shells, it was possible to observe both the bed and suspended load in movement during flume operation.
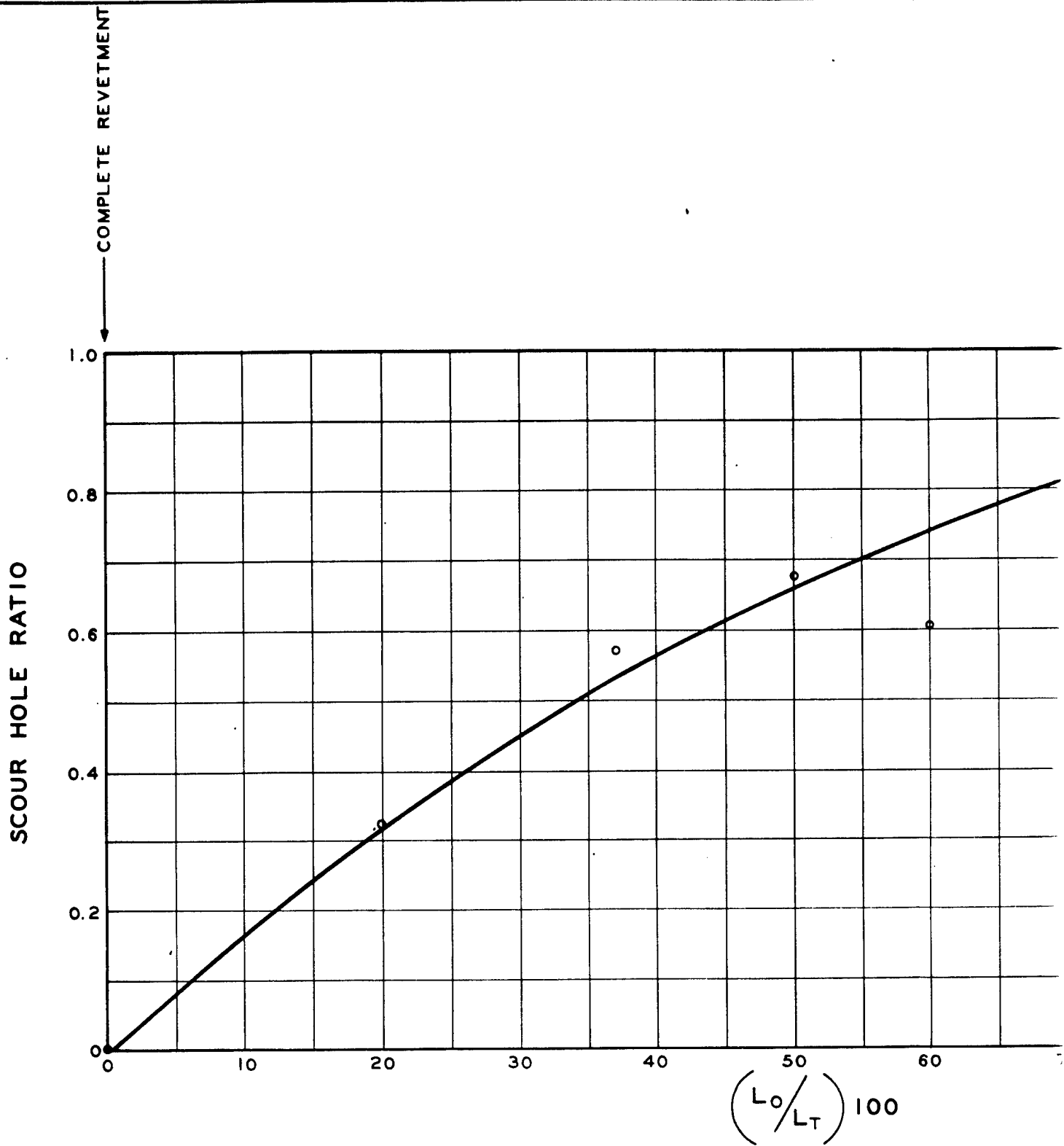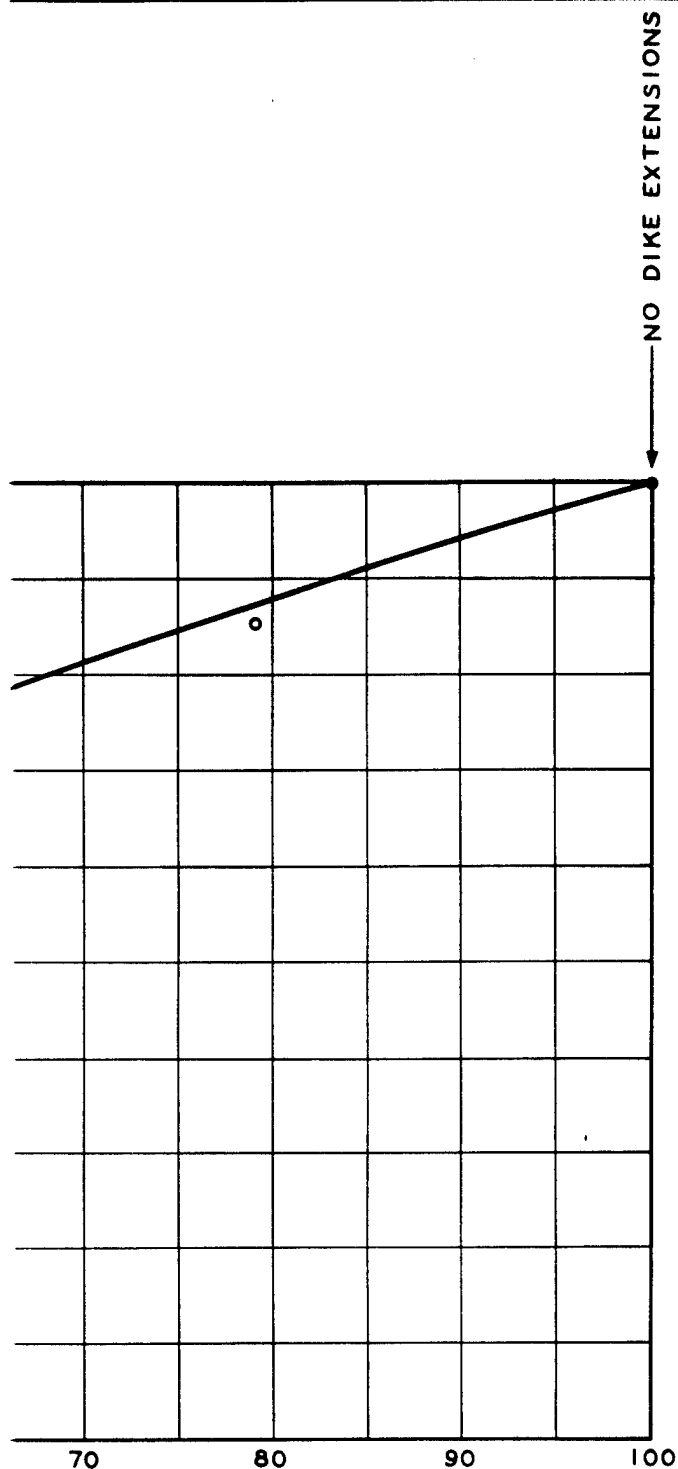
COMPLETE REVETMENT

$$\left(\frac{\text{AVERAGE DEPTH}}{\text{AVERAGE DEPTH WITH NO DIKE EXTENSIONS}}\right)100$$

$$\left(\frac{\text{DIKE EXPOSURE}}{\text{TOTAL POSSIBLE EXPOSURE}}\right)100$$

①

NO DIKE EXTENSIONS

DIRECTION OF FLOW

SPUR DIKES

E_X = DIKE EXPOSURE

E_T = TOTAL POSSIBLE EXPOSURE

70   80   90   100

100

MISSOURI RIVER DESIGN STUDY
AVERAGE DEPTH RATIO
VS.
EXPOSURE RATIO

U.S. ARMY ENGINEER DISTRICT,   OMAHA
CORPS OF ENGINEERS OMAHA, NEBRASKA
MAY 1964

PLATE VI

②

COMPLETE REVETMENT

SCOUR HOLE RATIO

$\left(L_O/L_T\right) 100$

①

$$\text{SCOUR HOLE RATIO} = \frac{L_X}{L_X @ 100 \% \text{ GAP}}$$

OUTER LIMITS
OF SCOUR HOLE

DIRECTION OF FLOW

L_X

L_T

L_O

SPUR DIKES

SPUR DIKE PLAN

o   DATA FROM TEST SERIES NO 2

70   80   90   100
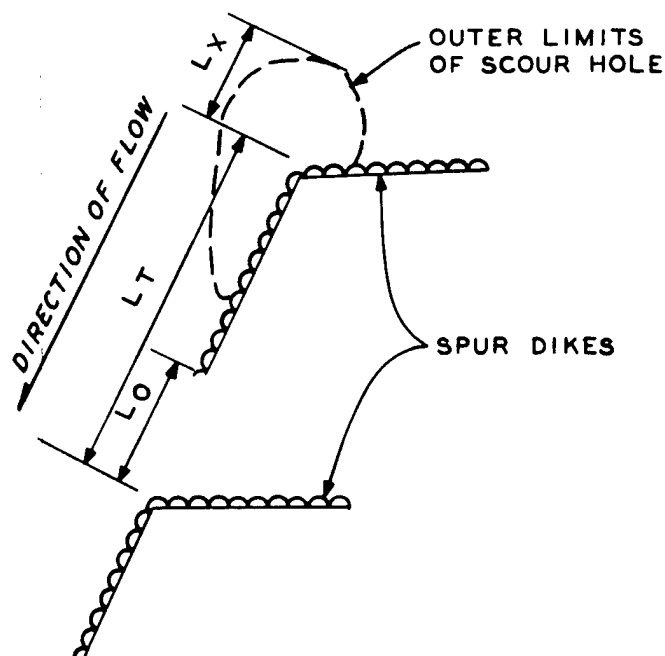
MISSOURI RIVER DESIGN STUDY
SCOUR HOLE RATIO
VS.
PERCENT OPENING

PLATE VII

COMPUTED MANNINGS "n" VALUE

$\left(\dfrac{\text{DIKE EXPOSURE}}{\text{TOTAL POSSIBLE EXPOSURE}}\right)$ 10(
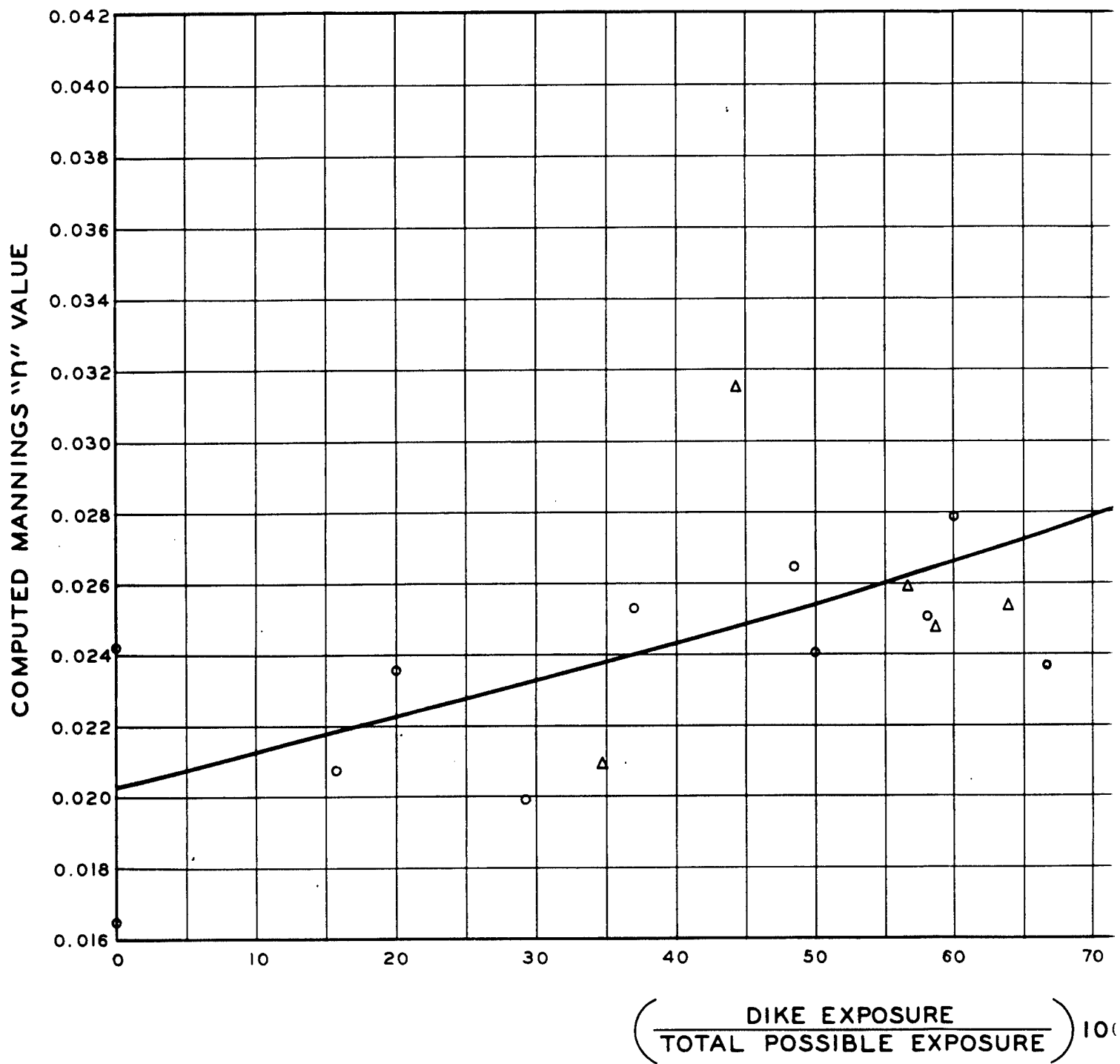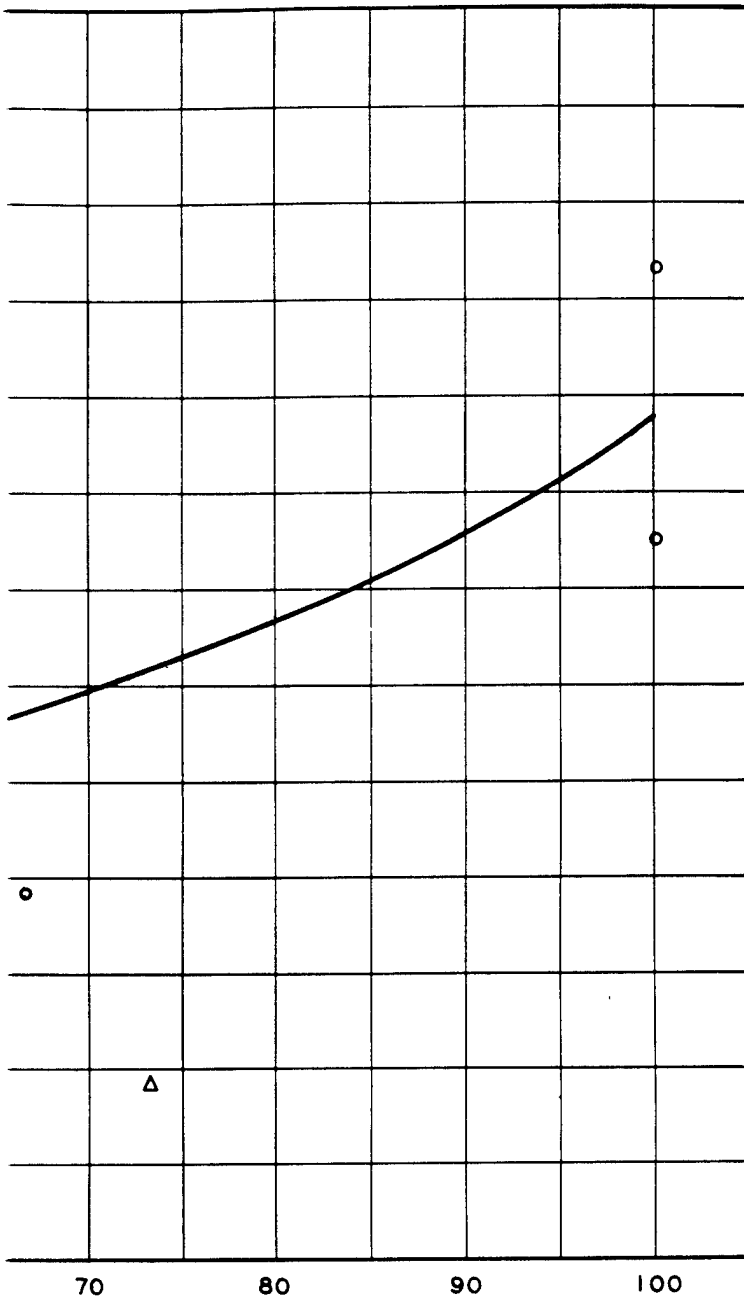
o   TEST SERIES 1 & 2

Δ   TEST SERIES 3
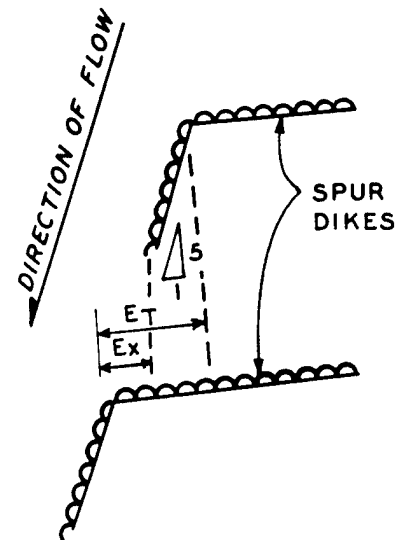
DIRECTION OF FLOW

SPUR DIKES

E_T

E_x

5

E_X = DIKE EXPOSURE

E_T = TOTAL POSSIBLE EXPOSURE

70   80   90   100

$\left.\dfrac{E_x}{E_T}\right) 100$

MISSOURI RIVER DESIGN STUDY
DIKE EXPOSURE RATIO
VS.
MANNINGS "n" VALUE

PLATE VIII
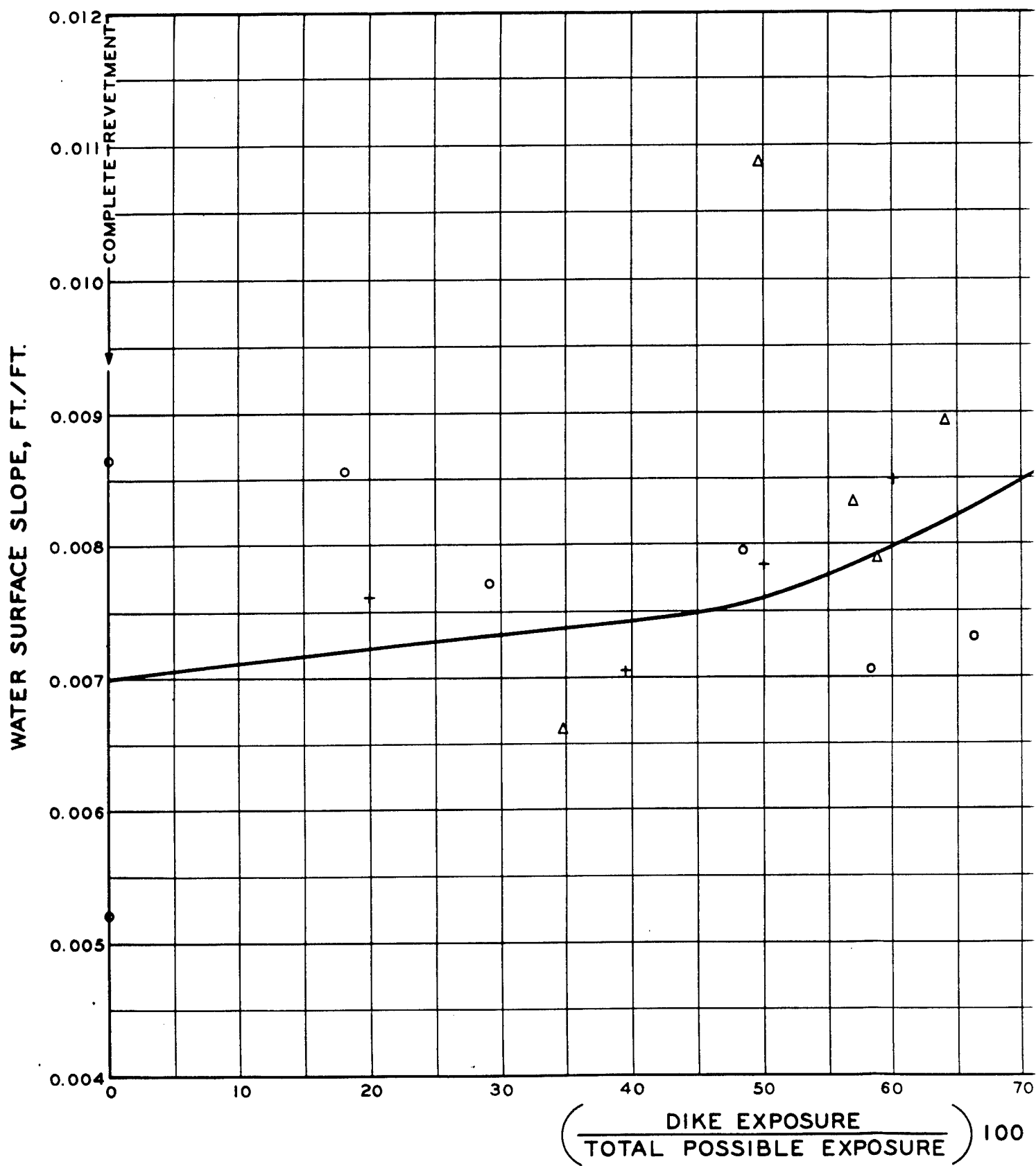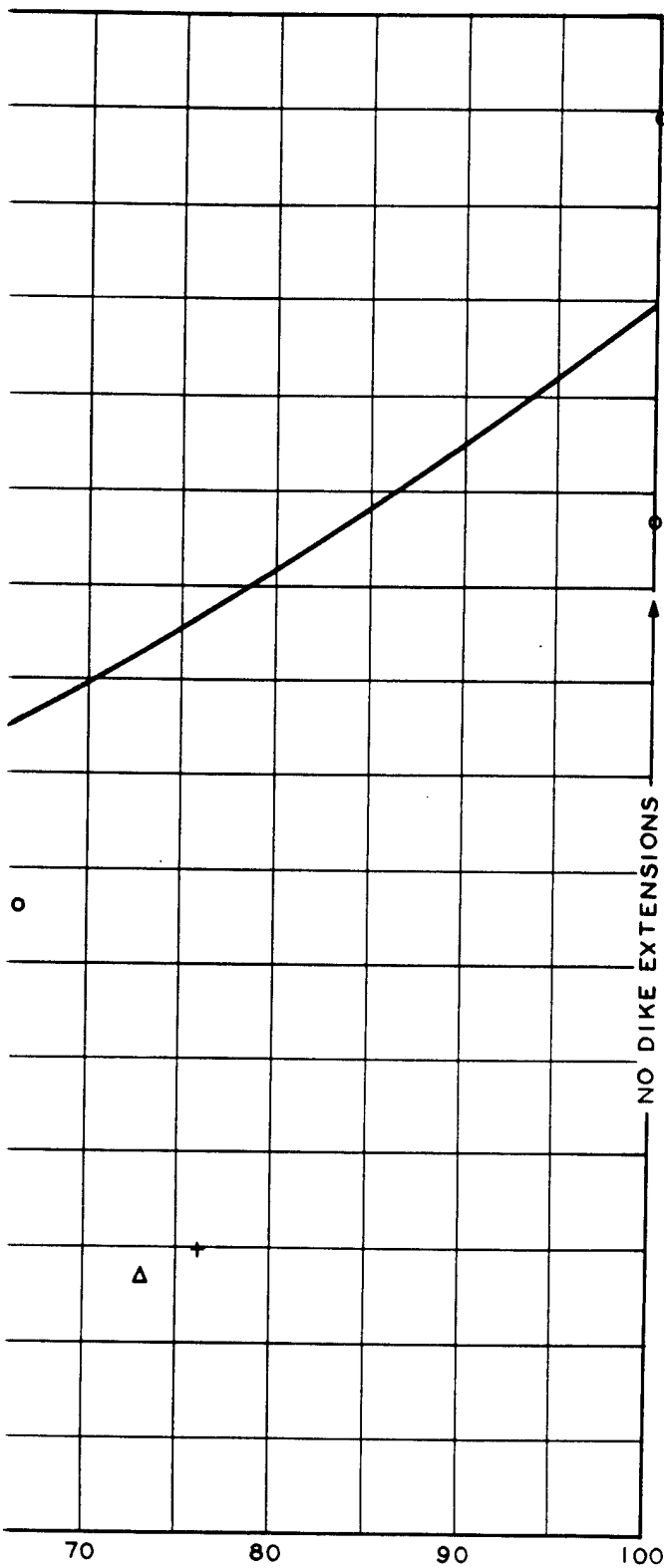
o   TEST SERIES NO. 1
+   TEST SERIES NO. 2
Δ   TEST SERIES NO. 3
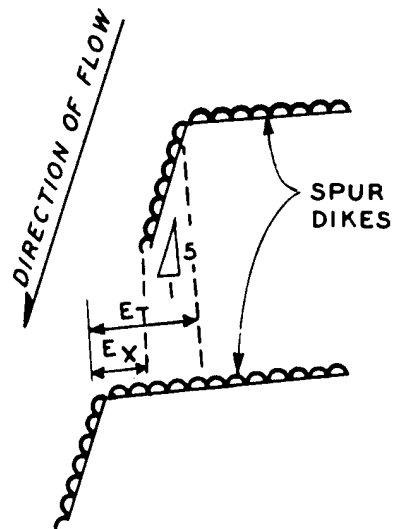
NO DIKE EXTENSIONS

DIRECTION OF FLOW

SPUR
DIKES

E_T

E_X

5

E_X = DIKE EXPOSURE
E_T = TOTAL POSSIBLE EXPOSURE

70   80   90   100

1100

MISSOURI RIVER DESIGN STUDY
DIKE EXPOSURE RATIO
VS.
WATER SURFACE SLOPE
U.S. ARMY ENGINEER DISTRICT, OMAHA
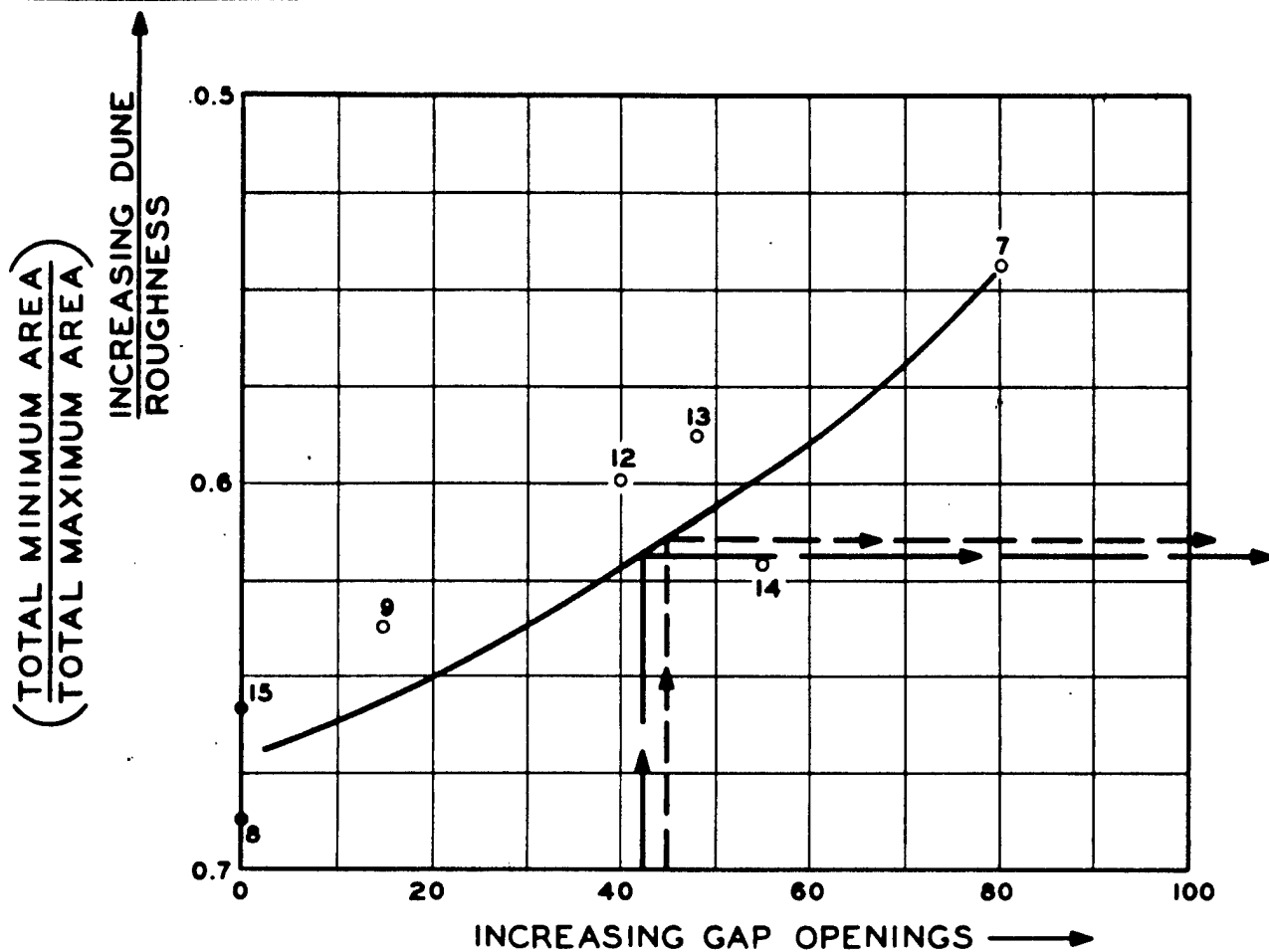CORPS OF ENGINEERS OMAHA, NEBRASKA
MAY 1964

PLATE IX

GAP OPENING AS A PERCENT OF CHANNEL WIDTH
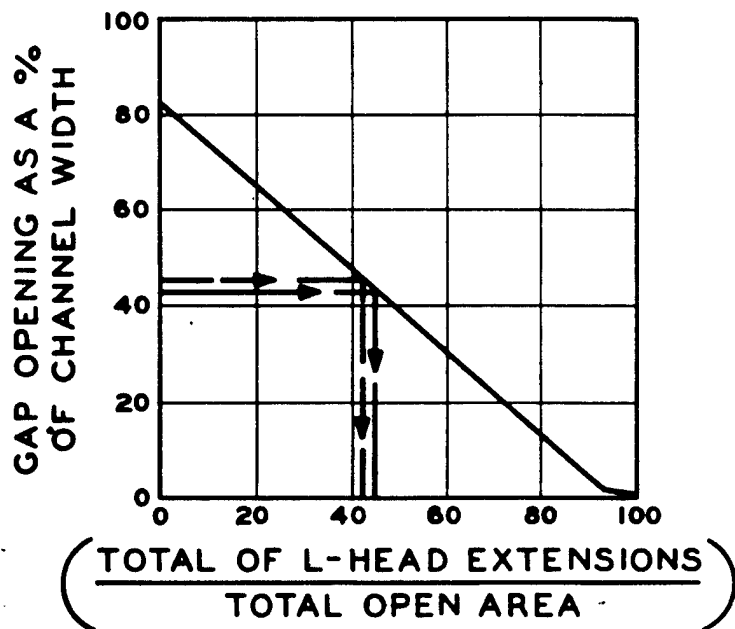FIGURE I (GRAPH OF ROUGHNESS VS GAP OPENING)

FIGURE 3 (GRAPH TO CONVERT FROM %
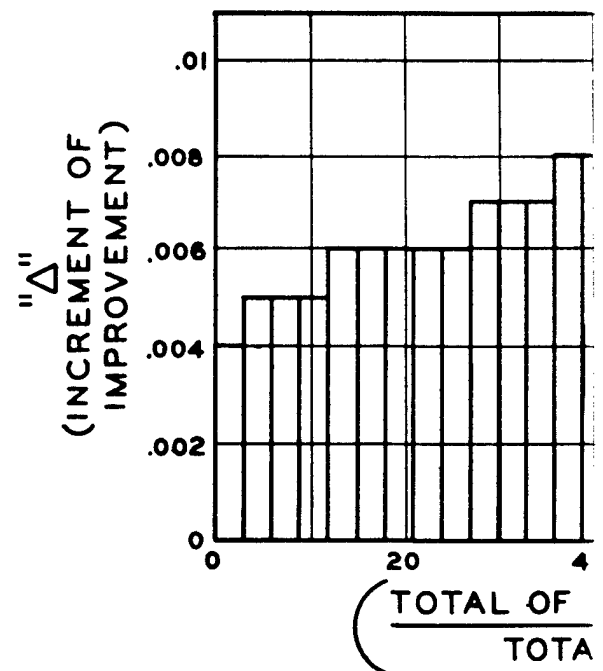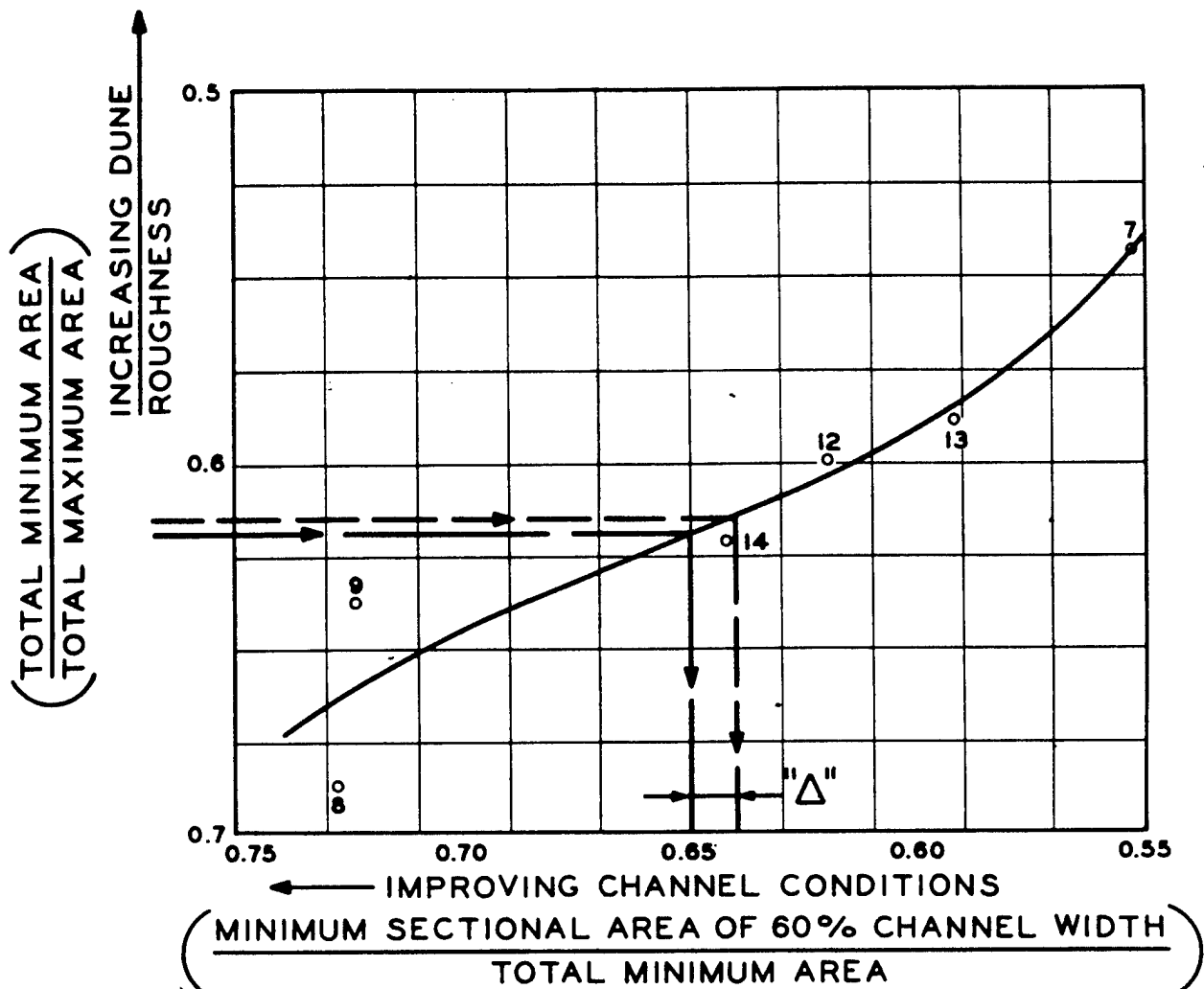GAP OPENING TO % TOTAL L-HEADS)

FIGURE 4 (GRAPH
VS % TOTAL

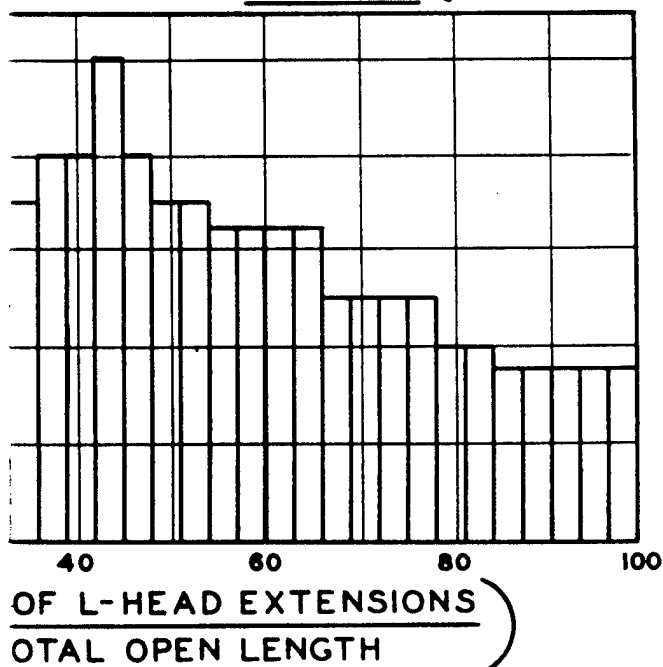FIGURE 2 (GRAPH OF ROUGHNESS VS USABLE CHANNEL RATIO)

$$\left(\frac{\text{OF L-HEAD EXTENSIONS}}{\text{OTAL OPEN LENGTH}}\right)$$

PH OF INCREMENT IMPROVEMENT
TAL L-HEAD EXTENSIONS)

MISSOURI RIVER DESIGN STUDY

L-HEAD INFLUENCE ON NAVIGATION
CHANNEL CONDITION

U.S. ARMY ENGINEER DISTRICT, OMAHA
CORPS OF ENGINEERS OMAHA NEBRASKA
JUNE 1964

The ability to observe underwater flow patterns both within the designed channel area and landward around the various structures makes this modeling technique a valuable tool to the engineer in developing the ultimate in structure designs. It was possible to watch the complete area development of the bed character as affected by a particular structure.

Various dune patterns, bed waves, current boils moved through the test area and presented to the observer a perspective that would be impossible to obtain of the prototype. Erosion and accretion characteristics along the banks of the model area were amazingly realistic to such actions observed along the natural river.

The phenomenon of bed armoring was noted in the sediment feed elevator when salvaged sediment material was used which contained a small amount of sand used in other laboratory work. Observations indicated that armoring of the bed to refuse degradation was obtained with only a very thin layer of heavy material.

Special tests were run during the investigation to observe the two separate bed regimes which involve a rough dune pattern and a smooth bed channel. By varying the induced sediment transport, it was possible to observe the transformtion from the rough bed with little sediment transport to the smooth bed formation with a heavy sediment transport.

General observations were recorded by operating personnel following each test run. This accumulated experience gained through operational observation was a significant factor in scheduling the course of the overall investigation.

8. Conclusion. Two very important factors in future design application should be considered before presenting the conclusions. First, the testing was limited to an investigation of a bend which falls into the median range curvature and therefore the results do not directly apply to the very sharp or very flat bends within the project. Second, dike spacing is an independent design consideration for each bend and, although greatly influenced by the bend curvature, individual dike spacings are determined from the inter-relationship of the upstream and downstream control requirements necessary to develop an integrated channel control network which is also mutually protective. This results in variable dike spacing within a control system as well as between bends.

The previously presented analysis indicates that a minimum of 50 per cent of the opening between spur dikes should be enclosed by L-head extensions to obtain the most economical improvement in reducing channel bed roughness. Data also indicated the initial 30 percent of L-head construction was very influencial in decreasing the scour around the spur dike ends by significantly reducing the intensity of the eddy flow pattern and that the effectiveness of the L-head extensions begins to diminish after approximately 65 percent of the opening has been closed. At this point dike spacing becomes an important consideration for the resultant gap with a 50 percent closure could exceed the desired individual boundary roughness opening. To further qualify the minimum

length of economical L-head construction the total length of closing structures within an overall spur dike system should eliminate at least 45 percent of the total open area between the dikes. When considering the aspect of total length of closure it should be mentioned that the indicated rate of channel improvement per unit of overall structure length was greatest from 27 percent to 67 percent of total extension construction.

The test data relating to the most economical height or crown elevation of L-head structures indicated very little benefit was derived in reducing bed roughness by construction above the water surface. Data indicated that approximately three feet of moving water could be allowed to overtop the structure without reducing the efficiency of the structure in improving the channel. L-head construction on the actual river at this location selected for modeling was built to water surface and a recent site inspection revealed that within the one year that the L-heads have been in place accretion has accumulated to an elevation just below water surface behind the structures. Although the navigation channel area is not substantially improved by construction to or above water surface the long range objective of land area reclamation and reduced structure maintenance must also be considered. The most realistic conclusion regarding height construction would be to phase the construction by initially constructing to within three feet of the navigation flows. When accretion has accumulated landward raise the structure to control the final increment of flow and provide for continued accretion build up which would result from periodic higher stages.

Laboratory time was not available to make tests regarding phase construction; however, data indicates that the L-head lengths as well as the height could be economically constructed in phases where immediate total improvement is not critical in obtaining project controlling depths.

Potential uses of such a facility are varied and future investigations could be made to gain additional information regarding the following general areas of design:

(1) Channel crossing studies where improvement is needed to provide more effective stable crossing control. This type of construction is expensive and exerts a strong influence on the channel through the downstream bend.

(2) Structure layout studies where the thalweg meanders within a long reach or bend. Such studies would assist in defining the most effective structure location and length along the convex side of the bend.

(3) Studies for improving very sharp bends where navigation channel is narrow and deep. This could involve two probable types of structures the channel sill and a boundary roughness dike both of which present a very critical layout problem.

(4) Study of the rate of bend curvature with an objective toward improving curve alignment in conjunction with thalweg meander in long reaches mentioned in (2) above.

(5) Additional L-head structure studies in bends of extreme sharp and flat curvature.

(6) Studies to continue to improve present structures in use and develop new structure types such as (a) convex and concave underwater sills, (b) structures on a curved alignment, (c) L-heads on different designed alignment, (d) dikes with sloping top elevation.

(7) Studies of dredging procedures to develop most effective method of opening a shoal area and following cut sequence. Downstream effects caused by changes in sediment transport due to dredging and spoil disposal.

(8) Studies to improve overbank flow characteristics of structure designs and high water influence to establish optimum Harbor Line locations.

(9) Studies relating to overall changes in water surface slope to provide earlier establishment of structure elevation criteria modifications.

(10) All above studies can be extended to cover the construction procedure regarding sequence and phase construction.

From the first preliminary tests through to the final run, the observational capabilities provided by the model during operation demonstrated a real future value of such a testing technique to the design engineer in progressive investigations aimed toward economical and successful development of river control structures.